Design and Implementation of a 5x5x5 LED Cube Display Showcasing Miller Indices using Arduino Mega

Submitted in partial fulfillment of the requirements of

Engineering Physics (BS15P)

for

First Year of Electronics and Telecommunication Engineering

By

Mr. Aaryan Purav 23104B0005
Ms. Tanisha Prajapati 23104B0038
Mr. Ayush More 23104B0065

Under the Guidance of

Prof. Ameya Nyayadhish

Department of First Year Engineering

VIT Vidyalankar Institute of Technology
Accredited A+ by NAAC

(An Autonomous Institute Affiliated to University of Mumbai)

Vidyalankar Institute of Technology
Wadala (E), Mumbai-400437

University of Mumbai

2023-24

CERTIFICATE OF APPROVAL

This is to certify that the project entitled

"Design and Implementation of a 5x5x5 LED Cube Display Showcasing Miller Indices using Arduino Mega"

is a bonafide work of

Mr. Aaryan Purav 23104B0005
Ms. Tanisha Prajapati 23104B0038
Mr. Ayush More 23104B0065

submitted to the University of Mumbai in partial fulfillment of

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Guide (Name) | Head of Department | Principal

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Name of student	Roll No.	Signature
1) Mr. Aaryan Purav	23104B0005	
2) Ms. Tanisha Prajapati	23104B0038	
3) Mr. Ayush More	23104B0065	

Date:

Place:

Acknowledgements

This Project wouldn't have been possible without the support, assistance, and guidance of a number of people whom we would like to express our gratitude to. First, we would like to convey our gratitude and regards to our mentor **Prof. Ameya Nyayadhish** for guiding us with his constructive and valuable feedback and for his time and efforts. It was a great privilege to work and study under his guidance.

We would like to extend our heartfelt thanks to our Head of Department, **HOD, Ms. Sonaali Borkar** for overseeing this initiative which will in turn provide every Vidyalankar student a distinctive competitive edge over others.

We appreciate everyone who spared time from their busy schedules and participated in the survey. Lastly, we are extremely grateful to all those who have contributed and shared their useful insights throughout the entire process and helped us acquire the right direction during this research project.

Abstract

This project presents the design and construction of a **5x5x5 LED Cube** as a three-dimensional visualization tool for **Miller Indices**, an essential concept in crystallography and solid-state physics. Miller Indices describe the orientation of atomic planes in a crystal lattice, but these concepts are traditionally taught using two-dimensional diagrams, which limit students' spatial understanding. The LED Cube bridges this gap by allowing real-time, dynamic 3D visualization of these indices through animated light patterns.

The cube comprises **125 LEDs** arranged in 5 layers of 5x5 matrices. Each LED represents a point in 3D space. By activating specific sets of LEDs in programmed sequences, the cube can simulate crystallographic planes such as (100), (110), and (111). These animations not only help visualize symmetry and structure but also make the learning experience engaging and memorable.

An **Arduino Mega** microcontroller is used for control due to its large number of GPIO pins, which eliminates the need for shift registers or external multiplexers. All animations are written in **C/C++ using Arduino IDE**, and timing is handled through software-based loops rather than hardware timer interrupts.

In addition to its educational role, the cube provides an excellent platform for learning embedded systems, circuit design, and programming logic. The integration of hardware and software makes it a valuable hands-on project for engineering students and hobbyists interested in microcontrollers and electronic display systems.

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INTRODUCTION

1.1 Background

Crystallography is a fundamental topic in materials science and solid-state physics that involves the study of crystal structures and their geometric arrangements. One of the key tools in this domain is **Miller Indices**, which define the orientation of crystal planes using a set of three integers. Understanding these indices is essential for fields such as nanotechnology, semiconductor physics, and metallurgy.

However, traditional teaching tools like books, chalkboards, and 2D images fail to convey the true spatial nature of these planes. Students often struggle to mentally visualize how these abstract numbers correspond to actual planes in a 3D structure. This leads to conceptual gaps and difficulty in applying this knowledge practically.

1.2 Objective

This project addresses the above challenge by creating a **physical 3D LED matrix** that can simulate the arrangement and movement of planes described by Miller Indices. By physically lighting up planes in a cubic LED structure, students can intuitively understand how (100), (110), and (111) planes slice through a lattice.

1.3 Why an LED Cube?

The LED Cube is a powerful 3D display medium, often used in art installations and electronic visualizations. It is capable of creating animations in real-world space, which is ideal for educational demonstrations. Unlike 2D displays, it provides depth and movement, allowing users to view dynamic transitions from different angles.

In this project, the **5x5x5 LED Cube** serves as both a demonstration tool and a mini embedded system project. It involves:

- Physical construction (soldering, grid alignment)
- Microcontroller interfacing (pin mapping, current limiting)
- Animation design (Miller Indices pattern logic)
- Embedded programming

1.4 Relevance to Engineering Curriculum

This mini-project aligns with subjects like **Analog & Digital Electronics**, **Embedded Systems**, and **Solid State Devices**. It also strengthens skills in teamwork, documentation, presentation, and problem-solving — key outcomes expected from project-based learning.

1.5 Scope of the Project

- To physically construct a 3D LED Cube (5x5x5) using simple, inexpensive components.
- To develop animations that visually demonstrate Miller Indices and 3D geometric patterns.
- To create a tool that can be used in classrooms and labs for teaching crystallography.
- To explore power management, GPIO limitations, and coding practices in Arduino.

LITERATURE SURVEY

2.1 Literature Review

The concept of LED cubes has long been explored in educational, artistic, and technical domains. In recent years, such systems have evolved from simple blinking displays to sophisticated 3D visual tools capable of simulating spatial patterns and animations.

2.1.1 LED Cubes as Educational Tools

Studies such as the one by T. Wang et al. (2017) on "Visualizing Data in 3D LED Matrices" highlight the use of LED cubes in educational environments for teaching mathematics, physics, and computer science. These studies show that students exposed to real-time 3D simulations have significantly better spatial reasoning and retention of abstract concepts.
Educational institutions increasingly advocate for active learning and STEM-based project modules. LED cubes allow students to engage with hardware and software simultaneously, bridging the gap between theoretical learning and practical implementation.

2.1.2 Arduino-Based Interactive Systems

The use of Arduino in academic projects has become ubiquitous due to its ease of use, open-source nature, and extensive online community. As per Banzi and Shiloh's work (*Getting Started with Arduino*, 2014), Arduino boards provide an excellent platform for rapid prototyping, especially when it comes to controlling large numbers of I/O devices like LEDs.
Several projects and tutorials available online guide the construction of 3x3x3 and 4x4x4 LED cubes using shift registers or LED drivers. However, the use of direct GPIO control with higher-end boards like Arduino Mega, as done in this project, offers both simplicity and greater educational clarity, avoiding added complexity from external ICs.

2.1.3 Miller Indices Visualization

Miller Indices are a cornerstone of crystallography and are covered extensively in materials science textbooks like *Solid State Physics* by Ashcroft & Mermin (1976) and *Condensed Matter Physics* by Marder (2010). These indices describe planes in crystal lattices but are traditionally taught using flat 2D sketches in textbooks.
Despite their foundational importance, there are limited tools available that allow for interactive 3D visualization of these planes. Most 3D software simulations (like CrystalMaker or XRD Viewer) are either proprietary or too advanced for undergraduate learners.
Thus, there is a growing interest in low-cost, physical demonstrators that can make such abstract concepts intuitive — this project being a direct response to that need.

2.2 Problem Formulation

While Miller Indices play a vital role in understanding crystallographic structures, they remain difficult to teach and understand using conventional methods. Classrooms typically rely on sketches or digital simulations that fail to provide a tactile or immersive understanding.

Commercial 3D display systems and scientific visualization software are either too expensive or lack the flexibility for custom educational content. Additionally, they often require a steep learning curve and are not feasible in resource-constrained institutions.

This project formulates the following key problem statements:

1. Visualization Gap:
   There is a lack of physical, interactive tools for understanding Miller Indices and 3D crystallographic planes in real-time.
2. Accessibility:
   Most available technologies are either cost-prohibitive or impractical for use in undergraduate labs or high school settings.
3. Over-reliance on Software:
   Current tools are mostly software-based and do not provide a hands-on electronics learning opportunity.
4. Pedagogical Limitation:
   Traditional teaching approaches fail to accommodate kinesthetic and visual learners who benefit from interactive demonstrations.

METHODOLOGY

3.1 Development Strategy

The implementation of the 5x5x5 LED Cube project involved a structured workflow covering multiple stages from concept to testing. The methodology followed is as below:

Step 1: Planning & Design

- Defined the purpose: to visualize Miller Indices in 3D.
- Decided on a 5x5x5 layout for balance between visibility, wiring simplicity, and code scalability.
- Chose white LEDs for their brightness and neutrality, suitable for clear visibility in educational demos.

Step 2: Component Selection

- Selected the Arduino Mega due to its large number of GPIO pins (54 digital + 16 analog), eliminating the need for shift registers.
- Used standard 5mm white LEDs with forward voltage of ~3.0V and current ~20mA.
- Chose resistors to limit current, single-core hookup wires, and perfboards for clean layer construction.

Step 3: Hardware Construction

- LEDs were grouped into 5 horizontal layers (Z-axis), each containing 25 LEDs (5x5 grid).
- All anodes in each (X-Y) layer were connected to dedicated digital pins on Arduino Mega (using anodePins[][]).
- All cathodes of LEDs in the same Z-layer were connected together and wired to a single analog pin (layerPins[]) acting as a common cathode (active LOW).
- Used A0 to A4 for controlling 5 Z-layers, and GPIO 22 to 12 for anode matrix mapping.

Step 4: Software Design and Programming

The Arduino code was written in C++ using Arduino IDE, structured into:

- Setup(): Initializes all pins as OUTPUT, sets anodes to LOW and cathodes to HIGH (inactive).
- Loop(): Cycles through animations for common Miller planes — (100), (010), (001), (110), (101), (011), (111).
- Functions:
  - showPlane100(), showPlane010(), etc., each light up the cube to display a crystallographic plane.
  - turnOffAll(): utility function to reset anode states before switching planes.
- Multiplexing: Done manually in software — layers are activated one at a time, while corresponding LEDs are pulsed ON to simulate persistence of vision.

Step 5: Testing & Debugging

- Each layer was tested individually for shorts or misplaced LEDs.
- Used digitalWrite() logic to validate the correct pins were triggering expected LED patterns.
- Observed and corrected issues such as ghosting (LEDs faintly glowing when off), which was resolved by improving grounding and isolating layer activation sequences.
- Verified each Miller Index plane by comparing the physical display with theoretical diagrams.

3.2 List of Components and Specifications

Sr. No.	Component	Specifications	Quantity
1	Arduino Mega	ATmega2560 MCU, 54 digital I/O pins, 16 analog inputs, 5V logic	1
2	White LEDs	5mm, forward voltage 3.0V, forward current 20mA, viewing angle ~120°	125
3	Resistors	220Ω, ¼ watt (for current limiting on anode lines)	25
4	Jumper Wires	Single-core solid copper wires, various colors for clarity	As req.
5	Perfboard / Grid	Used to mount and align LED planes	1
6	USB Cable	Type-B USB cable for programming Arduino Mega	1
7	Power Supply	5V, 2A DC adapter (external, if not USB powered)	1
8	Soldering Kit	Soldering iron, solder wire, flux, and desoldering pump	1 set
9	Base Platform	Wooden or acrylic cube base to mount electronics securely	1

3.3 Arduino Code Implementation

```
// Define anode pins (X-Y grid: 5x5 = 25)
const int anodePins[5][5] = {
  {22, 24, 26, 28, 30},  // X = 0
  {32, 34, 36, 38, 40},  // X = 1
  {42, 44, 46, 48, 50},  // X = 2
  {52, 53, 5, 6, 7},     // X = 3
  {8, 9, 10, 11, 12}     // X = 4
};

// Define cathode layer pins (Z-axis)
const int layerPins[5] = {A0, A1, A2, A3, A4}; // Z = 0 to 4

void setup() {
  // Set anode pins as OUTPUT
  for (int x = 0; x < 5; x++) {
    for (int y = 0; y < 5; y++) {
      pinMode(anodePins[x][y], OUTPUT);
      digitalWrite(anodePins[x][y], LOW);
    }
  }

  // Set layer pins as OUTPUT
  for (int z = 0; z < 5; z++) {
    pinMode(layerPins[z], OUTPUT);
    digitalWrite(layerPins[z], HIGH); // HIGH = OFF (active LOW)
  }
}

void loop() {
  showPlane100(); delay(1000);
  showPlane010(); delay(1000);
  showPlane001(); delay(1000);
  showPlane110(); delay(1000);
  showPlane101(); delay(1000);
  showPlane011(); delay(1000);
  showPlane111(); delay(1000);
}

// Plane (100): x = constant
void showPlane100() {
  for (int x = 0; x < 5; x++) {
    for (int z = 0; z < 5; z++) {
      turnOffAll();
      digitalWrite(layerPins[z], LOW); // Activate layer z
      for (int y = 0; y < 5; y++) {
        digitalWrite(anodePins[x][y], HIGH);
      }
      delay(100);
      digitalWrite(layerPins[z], HIGH);
```

```
    }
  }
}

// Plane (010): y = constant
void showPlane010() {
  for (int y = 0; y < 5; y++) {
    for (int z = 0; z < 5; z++) {
      turnOffAll();
      digitalWrite(layerPins[z], LOW);
      for (int x = 0; x < 5; x++) {
        digitalWrite(anodePins[x][y], HIGH);
      }
      delay(100);
      digitalWrite(layerPins[z], HIGH);
    }
  }
}

// Plane (001): z = constant (entire layer)
void showPlane001() {
  for (int z = 0; z < 5; z++) {
    turnOffAll();
    digitalWrite(layerPins[z], LOW);
    for (int x = 0; x < 5; x++) {
      for (int y = 0; y < 5; y++) {
        digitalWrite(anodePins[x][y], HIGH);
      }
    }
    delay(500);
    digitalWrite(layerPins[z], HIGH);
  }
}

// Plane (110): x = y
void showPlane110() {
  for (int z = 0; z < 5; z++) {
    turnOffAll();
    digitalWrite(layerPins[z], LOW);
    for (int xy = 0; xy < 5; xy++) {
      digitalWrite(anodePins[xy][xy], HIGH);
    }
    delay(500);
    digitalWrite(layerPins[z], HIGH);
  }
}

// Plane (101): x = z
void showPlane101() {
  for (int z = 0; z < 5; z++) {
    turnOffAll();
    digitalWrite(layerPins[z], LOW);
```

```
    for (int x = 0; x < 5; x++) {
      digitalWrite(anodePins[x][z], HIGH);
    }
    delay(500);
    digitalWrite(layerPins[z], HIGH);
  }
}

// Plane (011): y = z
void showPlane011() {
  for (int z = 0; z < 5; z++) {
    turnOffAll();
    digitalWrite(layerPins[z], LOW);
    for (int y = 0; y < 5; y++) {
      digitalWrite(anodePins[z][y], HIGH);
    }
    delay(500);
    digitalWrite(layerPins[z], HIGH);
  }
}

// Plane (111): x = y = z
void showPlane111() {
  for (int z = 0; z < 5; z++) {
    turnOffAll();
    digitalWrite(layerPins[z], LOW);
    digitalWrite(anodePins[z][z], HIGH);
    delay(300);
    digitalWrite(layerPins[z], HIGH);
  }
}

// Helper: Turn off all anodes
void turnOffAll() {
  for (int x = 0; x < 5; x++) {
    for (int y = 0; y < 5; y++) {
      digitalWrite(anodePins[x][y], LOW);
    }
  }
}
```

This Arduino program controls a **5x5x5 LED Cube** for visualizing **Miller Indices** by lighting up specific planes in 3D space. The cube consists of 125 white LEDs arranged in a 3D grid, where each LED is addressed by its (X, Y, Z) coordinate.

Core Logic

- **Anode Matrix (X-Y Grid)**:
  Anodes of the LEDs are arranged in a 5x5 grid for each of the 5 layers. The array anodePins[5][5] stores the digital pins used to control each column in every layer.
- **Cathode Layers (Z-Axis)**:
  The cathodes of LEDs in each horizontal layer are grouped and connected to analog pins A0–A4. Only one layer is turned ON (set LOW) at a time for selective illumination — a technique known as **manual multiplexing**.
- **Setup Function**:
  - Initializes all anode and cathode pins as OUTPUT.
  - Ensures all LEDs are initially OFF (anodes LOW, cathodes HIGH).
- **Loop Function**:
  - Sequentially calls display functions for various Miller planes:
    - (100): Lights up columns where X is constant.
    - (010): Lights up rows where Y is constant.
    - (001): Activates entire horizontal layers (Z is constant).
    - (110), (101), (011): Diagonal planes based on linear combinations.
    - (111): Diagonal from corner to corner (X = Y = Z).

Plane Display Functions

Each function follows this pattern:

1. **Turn OFF** all LEDs using turnOffAll().
2. **Activate** one Z-layer by setting its cathode LOW.
3. **Illuminate** the target anodes that define the plane.
4. **Delay** for a short period to make the lighting visible.
5. **Turn OFF** the layer by setting its cathode HIGH again.

Utility Function

- turnOffAll() ensures all anodes are OFF before a new layer or pattern is displayed, preventing ghosting or undesired LEDs from lighting up.

This code demonstrates **efficient use of GPIO resources**, logical array-based pin mapping, and foundational concepts in **manual time-based multiplexing** — all of which are central to embedded systems and microcontroller-based design.

<u>Design & Working</u>

4.1 System Overview

The LED Cube is a 3D matrix of **125 white LEDs** arranged in a 5×5×5 structure (X-Y-Z axes). The cube is capable of displaying animations and patterns that simulate **Miller Indices**, making it a functional visual aid for crystallographic concepts. The **Arduino Mega** is used to control the cube, leveraging its high pin count for direct GPIO-based control without external components like shift registers.

The system design can be broken down into:

- Hardware design: Cube structure, wiring, and connections
- Software design: Control logic, animations, and visualization

4.2 Structural Design and Assembly

4.2.1 LED Arrangement

- **X-Y Grid (Anodes)**: Each of the 5 horizontal layers contains a **5x5 matrix** of LEDs, aligned in the X-Y plane. The anodes of each LED in the grid are connected to a dedicated digital pin on the Arduino Mega.
- **Z-Layers (Cathodes)**: The cathodes of all 25 LEDs in a horizontal plane (Z = constant) are connected together, forming a common cathode for each layer. These layers are individually activated using analog pins **A0–A4**, configured as digital outputs.

4.2.2 Physical Frame

- A **cube-shaped frame** was constructed using acrylic rods to maintain equidistant spacing between LEDs. Layers were first built on a perfboard or custom jig to ensure perfect alignment, and then stacked vertically.
- Each LED was **soldered in air** (freeform style) using precise bends in the leads to form a solid structural and electrical connection. Vertical spacing was ensured using spacers during construction.

4.3 Electrical Design

4.3.1 Multiplexing Concept

- Only **one Z-layer is active at a time** to avoid LED overlap or power draw issues.
- The cube uses **software-based multiplexing**, where each layer is rapidly activated and deactivated while displaying only the LEDs required for that instant.
- Persistence of Vision (POV) makes it appear as if the entire cube is lit simultaneously, though it's scanning each layer one at a time.

4.3.2 Power Considerations

- White LEDs typically require **~3.0V forward voltage** and **~20mA forward current**.
- A current-limiting resistor (~220Ω) is connected in series with each anode column to prevent excessive current.
- The cube is powered via USB or external 5V adapter; care was taken to ensure current consumption remains below the maximum allowable limits of Arduino Mega (total I/O current < 200mA for safety).

4.4 Software Design

The control program was written in **Arduino C++**, where:

- **Two arrays** (anodePins[5][5] and layerPins[5]) store the physical pin numbers for easy addressing.
- A series of **animation functions** (showPlane100(), showPlane111(), etc.) illuminate LEDs that represent specific crystallographic planes.
- A **helper function**, turnOffAll(), resets the state before each layer activation to avoid residual lighting or ghosting.

4.4.1 Plane Mapping Logic

Each function implements a plane visualization:

- (100) lights all LEDs with the same X-coordinate.
- (010) lights all LEDs with the same Y-coordinate.
- (001) lights all LEDs in a layer.
- (110), (101), (011), (111) represent diagonal planes and require conditional logic or pattern-based iteration.

The loop function cycles through these plane functions with delays to simulate smooth transitions between views.

4.5 Troubleshooting and Challenges

During the development phase, the following issues were identified and addressed:

Issue	**Diagnosis**	**Solution**
Ghosting (faint LED glow when off)	Improper reset of anodes	Used turnOffAll() before every activation
Short circuits	Inconsistent LED orientation during soldering	Created a jig to align all LEDs in the same direction
Power surges at startup	All layers briefly ON	Added delay in setup() and layered startup pattern
Unstable animations	Grounding issues and floating pins	Improved solder joints and used a single-point ground

4.6 Design Advantages

- **No external components** like shift registers: Makes learning and debugging simpler for students.
- **Scalable architecture**: The same design can be expanded to 6x6x6 or more with code and wiring changes.
- **Full control and customization**: Each LED can be individually addressed using GPIO logic without abstracted IC interfaces.

Chapter 5: Output & Results

5.1 Demonstrated Output

The completed 5x5x5 LED Cube successfully demonstrated real-time 3D animations of multiple **Miller Indices**. Each function displayed clear, observable lighting patterns that corresponded to crystallographic planes in a unit cell. The cube's lighting was stable, well-distributed, and consistently aligned with the programmed patterns.

The following plane visualizations were achieved:

Plane	Representation	Visual Pattern Description
(100)	X = constant	Vertical slices through the cube along the X-axis
(010)	Y = constant	Horizontal slices from front to back (Y-axis planes)
(001)	Z = constant	Entire horizontal layers lit up one at a time
(110)	X = Y	Diagonal patterns from top-front-left to bottom-back-right
(101)	X = Z	Diagonal from front-bottom to back-top layers
(011)	Y = Z	Diagonal sheets sloping across layers from side
(111)	X = Y = Z	Center-to-corner "space diagonal" lighting — highly visual and dramatic

Each of these patterns appeared for a short duration (~0.5s to 1s), then transitioned smoothly into the next, providing a **clear, animated demonstration** of how crystallographic planes intersect a 3D structure.

5.2 Pattern Behavior and Transitions

- **Timing**: Each function was given a specific delay to ensure that patterns were observable and not too fast for the human eye. Delays ranged between **100ms to 1000ms** depending on the complexity of the pattern.
- **Animation Fluidity**: Multiplexing created the illusion that all layers were active simultaneously due to the speed of human visual processing (Persistence of Vision). Even though only one layer was active at a time, viewers perceived continuous and fluid animation across the cube.
- **Plane Transitions**: After each plane visualization, the cube returned to an all-OFF state briefly, allowing the previous frame to fade and giving clarity to the next one. This minimized confusion between overlapping planes.

5.3 Educational Outcomes

The LED cube proved to be an **exceptional pedagogical tool**, especially for demonstrating abstract 3D concepts to students. Observers could directly relate the numeric Miller Indices to a **physical, glowing representation** of those planes.

Key observed learning benefits:

- **Improved spatial understanding** of crystallographic directions.
- **Visual engagement**: Students were more attentive and responsive during explanations involving the cube.
- **Intuitive learning**: Even those unfamiliar with Miller Indices could understand the concept when shown the cube's behavior.

This makes the cube highly effective for use in:

- Physics labs
- Material science workshops
- Embedded systems demonstrations
- Academic presentations

CONCLUSION

The **5x5x5 LED Cube** project successfully achieved its core objective: to create a functional, low-cost, and interactive platform for visualizing **Miller Indices** in three dimensions. Through a combination of hardware prototyping, embedded systems programming, and fundamental concepts from crystallography, this mini-project bridges the gap between theoretical abstraction and tangible understanding.

The cube displays clear, animated representations of planes such as (100), (010), (001), and even complex diagonals like (111), by manually multiplexing LEDs across 125 nodes using an Arduino Mega. The decision to use **direct GPIO control** without shift registers or timer interrupts made the system easier to build, debug, and understand — a significant advantage in academic environments where learning and clarity are prioritized.

The visual output of the cube served as a powerful **educational aid**, transforming abstract mathematical indices into real-time spatial representations. Students and viewers could observe and interpret crystallographic orientations intuitively — something not easily achievable with traditional diagrams or static slides.

From a technical perspective, the project deepened our understanding of:

- 3D circuit layout and wiring strategy
- Software-controlled multiplexing and visualization logic
- The real-world application of concepts like Miller Indices, timing, voltage/current control

Despite the relatively simple construction, the cube demonstrated how effective basic electronics and embedded coding can be in creating engaging, STEM-focused learning tools. It also laid a foundation for more advanced developments, such as:

- Scaling up to larger grids (6x6x6 or 8x8x8)
- Adding brightness control using PWM
- Integrating user interaction via buttons or mobile app control
- Real-time 3D plotting from scientific or sensor data

In conclusion, this project is not just an electronics build; it is a model of **applied interdisciplinary learning** — connecting physics, electronics, and programming in a creative and impactful way. It validates the power of experiential education and showcases how engineering can be both educational and inspiring.

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Skill Developed / learning outcome of this Engineering Physics –

The following skills were developed while performing and developing this mini-project

1. Embedded Programming
2. Circuit Design & Assembly
3. Multiplexing Logic
4. Power Management
5. Debugging & Troubleshooting
6. Problem Solving
7. Documentation & Reporting
8. Time Management
9. Team Collaboration
10. Presentation & Demonstration