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Research Article

User Friendly Interactive Digital Logic Trainer with Display

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Abstract

Digital logic education is a core element of computer engineering, yet many trainers rely on LED indicators that provide limited feedback, reducing students' ability to fully grasp circuit behavior. Such minimal demonstrations restrict the interpretation of input–output relationships in real time and lessen the value of practical training. This paper presents the design and implementation of a digital logic trainer with an integrated LCD display, specifically developed to enhance undergraduate learning. The trainer combines 74-series logic gate ICs with an ATmega328 microcontroller, navigation buttons, LED indicators, and a regulated 5V DC power supply, all mounted on a vero board within a protective casing. Programmed in the Arduino IDE, the microcontroller processes inputs and updates the LCD to show logic states, selected operations, and outputs. Unlike LED-only systems, the LCD provides contextual information, including truth table rows, thereby bridging theory and practice while improving clarity and retention.

1. Introduction

Digital logic is the foundation of modern electronics and computer systems. In academic settings, especially in electronics and computer engineering, students need to move beyond theory and engage with practical experiments to understand how logic circuits function [1]. This is where digital logic trainers come in. These trainers are hands-on educational tools used to demonstrate the behavior of basic logic gates such as AND, OR, NOT, NAND, NOR, and XOR. They allow students to build, observe, and troubleshoot real digital circuits, which helps bridge the gap between classroom learning and real-world applications [2].

Hands-on laboratory practice remains essential for mastering digital logic concepts such as Boolean algebra, truth tables, combinational and sequential circuits. However, practical delivery is frequently constrained by limited equipment and overcrowded labs in Nigerian universities and similar contexts. Recent analyses of STEM laboratories in Nigeria report shortages of equipment and high student-to-equipment ratios that hamper experiential learning and skill acquisition [1, 2].

In computer science and engineering education worldwide, there is a sustained emphasis on developing a strong foundation in digital systems and practical laboratory skills, underscoring the importance of effective instructional hardware to enhance conceptual understanding and technical proficiency [3, 4]. Conventional digital logic trainers that rely solely on LEDs provide limited binary feedback, making it

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difficult for learners to interpret input–output relationships or trace truth-table progressions in real time. To bridge this pedagogical gap, this study introduces a digital logic trainer that incorporates a character LCD capable of displaying real-time input states, selected logic operations, and corresponding outputs. This integration improves learners' interactive experience and reinforces conceptual understanding during laboratory exercises.

The Primary Contributions of this project is outlined below:

- An LCD-augmented trainer that couples discrete 74-series IC gates with a microcontroller for richer, contextual feedback.
- A modular architecture and firmware that display live input vectors and truth-table rows to scaffold conceptual understanding

2. Related Work

Digital logic trainers have evolved through distinct stages from mechanical relay-based systems to electronics-based designs, and now to hybrid and remotely accessible platforms. This section reviews that evolution, highlights recent improvements, and places the present work in context.

Early digital logic teaching tools (1950s–1960s) were primarily mechanical or relay-based systems, such as switch-and-lamp assemblies, used to demonstrate basic Boolean operations. With the emergence of integrated circuits (ICs) in the 1970s and 1980s, IC-based trainer kits became standard in engineering education. These trainers typically employed TTL and CMOS logic families, breadboards for circuit prototyping, and LEDs or bulbs for binary outputs, with students manually wiring gates and testing input combinations exhaustively. While these platforms improved learners' understanding of gate behavior and circuit interconnections, they suffered from key limitations: manual input testing was tedious, intermediate logic states were difficult to visualize, and the systems lacked programmability or real-time feedback.

Recent work in educational hardware for digital logic and systems training falls into four major categories:

1. **Microcontroller / Arduino-based trainers**
   Many modern trainers augment or emulate traditional logic kits using Arduino or ATmega microcontrollers. These systems provide a programmable control layer that reads switches, drives displays, and computes truth tables, while preserving physical interaction. For example, the "e-Logic Trainer Kit" uses an Arduino Mega 2560, keypad, and display to support combinational logic experiments and quiz modules. Users can simulate multiple logic combinations and receive feedback, bridging theory and practice [1]. Another design presents an Arduino-based training kit that supports analog and digital functions and has achieved validation for use in microcontroller courses [2].
2. **Energy-efficient and low-cost designs**
   To reduce the cost and power consumption of trainer kits, researchers emphasize the development of locally manufacturable and resource-aware designs. These efforts promote modular, low-power implementations (e.g., using vero boards, efficient regulators) that can be maintained locally without expensive imported parts. Such goals align with the constraints of many engineering labs in developing institutions.
3. **FPGA-based and remote FPGA laboratories**
   For advanced digital design, multiple institutions use FPGA platforms and remote labs. Students implement HDL modules and test them on real FPGA hardware remotely. A notable example is the FPGA-based remote laboratory developed by the University of Málaga, which allows students to configure FPGA modules remotely and test their designs in a real hardware environment [5]. Such platforms support sequential logic, timing analysis, and complex digital systems, complementing IC-level labs without replacing them.
4. **Cloud / IoT–integrated remote labs**
   The latest platforms integrate microcontrollers or single-board computers with web interfaces to provide remote access to real hardware. Students can configure inputs and observe outputs from remote locations, enabling hybrid learning. These systems improve accessibility, especially in situations where lab hours are limited or students cannot physically attend.

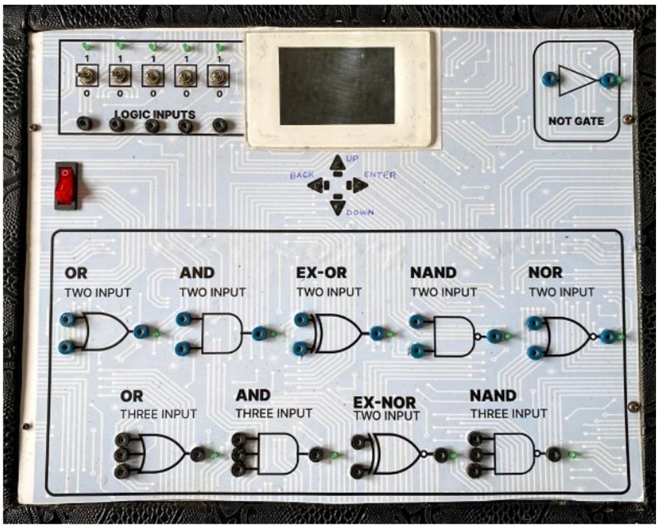

Figure 1: Digital Logic Trainers with LCD Display

This project adopts a hybrid architecture, combining the tangibility of discrete ICs and switches with the programmability of a microcontroller and visual feedback via an LCD. Unlike purely soft simulators or remote FPGA-only systems, our design preserves hands-on experience while providing real-time feedback and user-friendly usability. The locally assembled, vero-board implementation and regulated DC supply echo the low-cost and energy-aware design trend.

In summary, this work, as shown in Figure 1, fills a gap in existing literature by delivering a cost-effective, display-enabled, microcontroller-assisted, IC-interactive digital logic trainer that can serve as a platform for further enhancements (e.g., FPGA modules, remote access).

3. Methodology

The design of the digital logic trainer with display is grounded in the principles of Boolean algebra and digital logic theory, which define the operation of gates such as AND, OR, NOT, NAND, NOR, XOR, and XNOR. In an educational context, the constructivist theory of learning emphasizes practical experimentation as a means of enabling students to build knowledge through active engagement. Accordingly, the integration of both discrete logic circuits and a microcontroller-driven display provides a dual foundation: students experience the physical reality of IC-based logic while simultaneously receiving real-time interpretive feedback.

This dual approach aligns with the evolution of logic trainers discussed in the related work section, moving beyond earlier IC-only models to a hybrid system that strengthens both theoretical understanding and learner engagement.

3.1. System Architecture

The trainer adopts a hybrid architecture that combines hardware-based logic rigor with microcontroller-driven display intelligence. The block diagram Figure 2 illustrates the major subsystems, which include:

- **Input Section** with debounced toggle switches.
- **Logic Section** with 74-series ICs implementing discrete logic functions (e.g., 7408 AND, 7432 OR, 7404 NOT, 7486 XOR).
- **Processing Section** with an ATmega328P microcontroller for input scanning, logic simulation, and LCD interfacing.
- **Power Subsystem** with a linear 12/5 V supply. The ATmega328P provides 23 programmable I/O lines and operates at 12 V, suitable for direct interfacing with HC-TTL logic families [6, 7].
- **Display** – The 3.5-inch LCD, controlled via the HD44780 instruction set, displays input vectors, selected gate, and output bit, and can present truth-table row context [8].

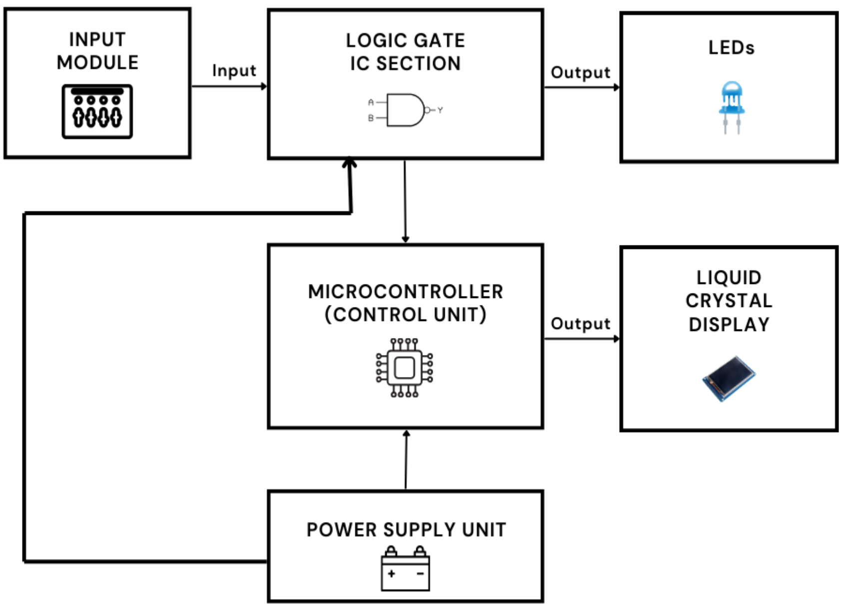

Figure 2: Block Diagram of the Digital Logic Trainer

3.2. Hardware

The hardware design of the digital logic trainer consists of five integrated modules:

- **Power Supply and Voltage Regulation:** Digital logic components operate at a stable voltage, typically 5V. To achieve this, the trainer includes a regulated power supply Figure 3 made up of:

  - **Transformer:** Steps down the 220V AC to a lower AC voltage.
  - **Bridge Rectifier:** Converts AC to DC.
  - **Capacitor:** Smoothens the fluctuating DC signal.
  - **7805, 7812 Voltage Regulators:** 7805 maintains a steady 5V output, suitable for TTL logic ICs and microcontrollers, while 7812 provides regulated voltage for the LCD display.

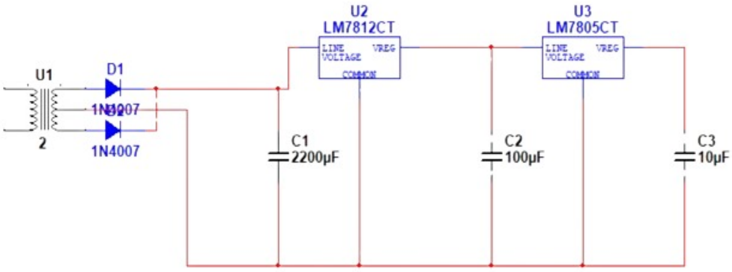

Figure 3: Block Diagram of Power Supply for the System

- **Input Section:** The input section consists of debounced toggle switches that allow the user to provide binary logic signals (0 or 1) to the trainer. Each switch is connected to a digital input pin of the ATmega328P microcontroller. Software debouncing is implemented in the firmware to eliminate errors caused by mechanical bouncing, ensuring reliable input detection. The switches are arranged clearly and labeled for each input variable (e.g., A, B, C) to facilitate ease of use during experiments. The input section is designed to interface directly with both the microcontroller and the 74HC-series logic ICs, providing flexible testing of combinational logic circuits.
  Technical Notes:
  - Each switch provides a logic HIGH (VCC) when pressed and logic LOW (0 V) when released.
  - Pull-down resistors (typically 10 kilo-ohms) are used to maintain stable LOW states when switches are open.
  - The microcontroller reads inputs at 5 V logic levels, compatible with TTL and CMOS logic families.
- **Logic ICs:** The core combinational functions are implemented with standard HC-family ICs. For example, SN74HC08 (AND) Figure 4 uses CMOS inputs with high impedance, supporting direct switch interfacing and MCU signaling; datasheets specify input models and absolute maximum ratings for safe operation [9]. SN74HC32 (OR), SN74HC04 (NOT), SN74HC86 (XOR) and derived NAND/NOR structures complete the gate set.

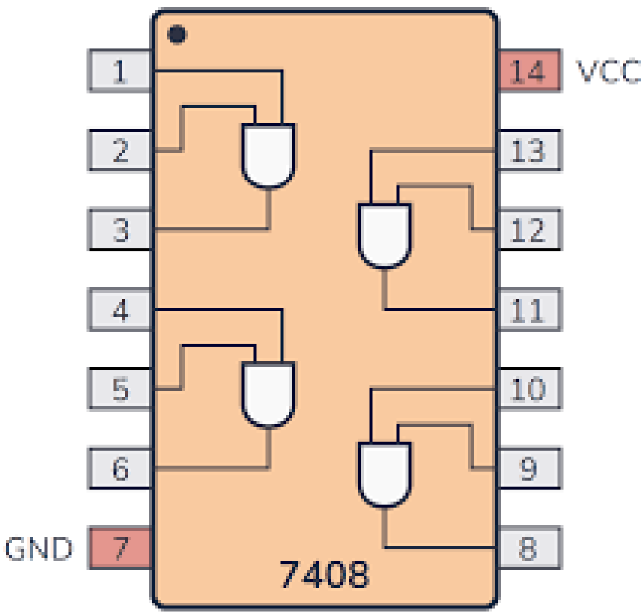

Figure 4: 74HC08 AND Gate Example Circuit

- **Microcontroller:** The ATmega328P microcontroller (Arduino-compatible) illustrated below in Figure 5 was chosen for its mature toolchain, 10-bit ADC (unused here), timers, and digital I/O count sufficient for switch scanning and LCD control. Microchip's datasheet notes operation from 2.7–5.5 V with automotive-grade temperature tolerance, improving robustness [6, 10]

A microcontroller makes the trainer smarter and more flexible Unlike ICs that perform fixed logic, a microcontroller can be programmed to simulate any logic function and even switch between them as needed [8].

In this project, the microcontroller was used to:

1. Read input values from switches.
2. Simulate the logic operation using code.
3. Send the result to the LCD display.
4. Display a mini truth table.

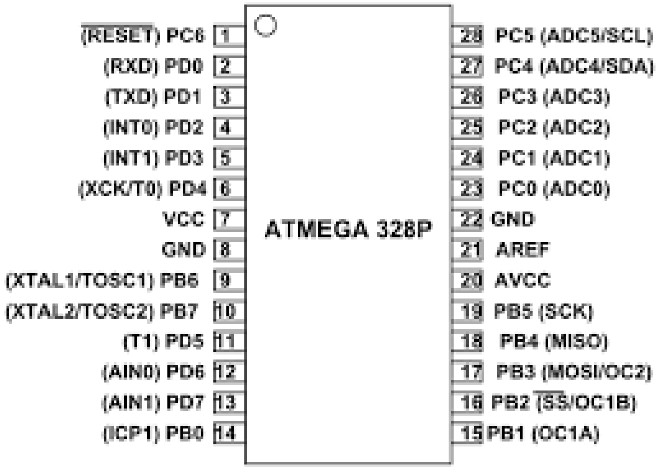

Figure 5: ATMega328P Pinout Diagram

- **LCD Interface:** The LCD Figure 6 is driven in 4-bit mode to conserve I/O. The HD44780 controller maps DDRAM addresses to display positions and supports cursor control and display shift, enabling compact display of inputs, gate type, and output bit [8, 11]. Rather than using LEDs to show output (which only indicate ON or OFF), the LCD gives a clearer picture of what's happening logically [12].

In this project, the LCD was used to:

1. Show current input states (e.g., A = 1, B = 0).
2. Indicate the logic function being performed.
3. Display the output result.
4. Sometimes show a short truth table or an explanation like: "Output is HIGH because A AND B are both HIGH." This helps users (especially beginners) understand why a result occurred, not just what the result was.

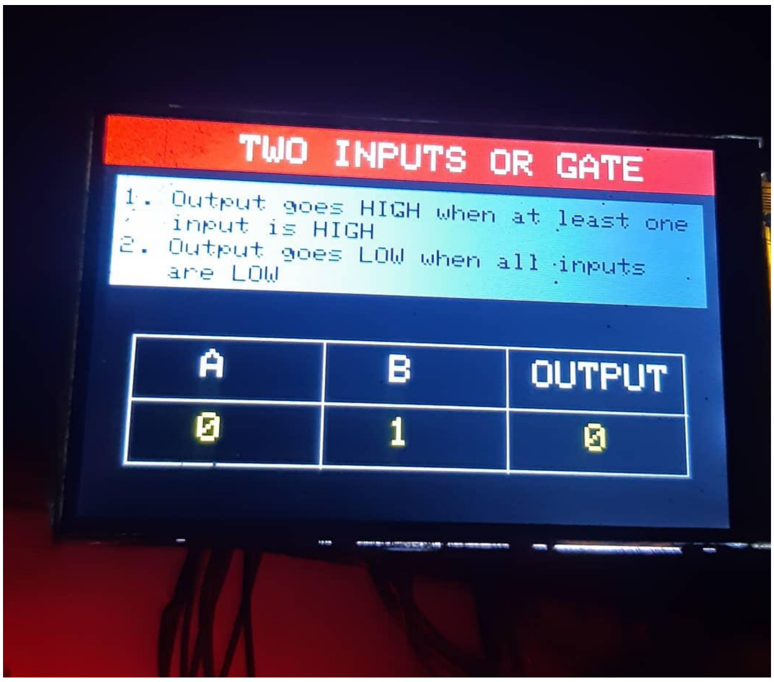

Figure 6: LCD showing logic inputs, operation, and output result

3.3. Firmware

The firmware for the trainer was developed in the Arduino IDE using C/C++. Its operation can be understood as a simple cycle: first, it reads the inputs from the toggle switches (with software debouncing to avoid errors from switch bounce). Next, it determines which logic gate has been selected and evaluates the output accordingly. The result is then shown on both the LED indicators and the LCD screen. Finally, the system checks whether any of the navigation buttons have been pressed to move between display options.

The LCD offers four main views for the user:

1. The current input values.
2. The selected logic gate.
3. The corresponding output.
4. The matching row of the truth table.

To ensure smooth operation, the display is refreshed in a time-safe way that prevents flickering, and the use of look-up tables allows the information from the truth table to be accessed quickly without slowing down the system.

3.4. Implementation

The prototype was built on a vero board and housed in a protective casing to ensure durability and safe handling. Ribbon cables were used to connect the toggle switches, logic IC sockets, and the LCD module, creating a neat and organized layout.

Each section of the trainer was clearly labeled to make it easier for students to identify components during use. The materials consisted of standard 74-series logic ICs, an ATmega328 microcontroller module, a 3.5-inch TFT LCD, passive components, a voltage regulator, toggle switches, and LEDs.

To make the design reproducible in other undergraduate laboratories, the assembly process was carefully documented step by step.

3.5. Evaluation Methodology

Functional tests verified each gate against canonical truth tables as shown in Table 1. For each input vector, LED output and LCD display content were recorded and compared with expected values. Stress tests included extended run-time to observe thermal and stability behavior. A formative classroom trial collected student feedback on clarity and engagement relative to LED-only trainers. Although virtual laboratories can complement hardware access, previous Nigerian studies emphasize persistent gaps in equipment and overcrowding, motivating tangible trainers to anchor foundational skills [1, 2].

Table 1: AND Gate Verification Results

Input A	Input B	Expected Output	Measured Output
0	0	0	0
0	1	0	0
1	0	0	0
1	1	1	1

4. Results and Discussion

This section presents the performance evaluation of the digital logic trainer, organized according to the methodology. The results include functional verification of logic gates, LCD display validation, microcontroller performance, and educational assessment. Each subsection is followed by discussion linking the observed results to the design objectives.

4.1. Functional Verification of Logic Gates

All implemented logic gates (AND, OR, NOT, XOR, NAND, NOR, XNOR) were tested against their canonical truth tables as in Table 2. Input vectors were applied using toggle switches, and outputs were recorded via LEDs and LCD display.

Table 2: AND Gate Verification Results

Input A	Input B	Expected Output	Measured Output
0	0	0	0
0	1	0	0
1	0	0	0
1	1	1	1

Discussion: The measured outputs for all logic gates matched the expected results, confirming correct hardware operation as shown in Table 3. The combination of 74HC-series ICs and the ATmega328P microcontroller ensured accurate computation of all logic functions. Stress tests indicated stable operation under continuous runtime conditions, highlighting system robustness.

Table 3: Summary of Logic Gate Verification

Logic Gate	Number of Tests	Accuracy (%)
AND	4	100
OR	4	100
NOT	2	100
XOR	4	100
NAND	4	100
NOR	4	100
XNOR	4	100

4.2. LCD Display Verification

The LCD module was tested to confirm proper visualization of:

1. Current input states (e.g., A = 1, B = 0),
2. Selected logic gate type,
3. Output result corresponding to the applied inputs,
4. Short truth table explanations when requested.

The display updated in real time without flickering, correctly reflecting all input and output states. This functionality aligns with the methodology step describing the microcontroller-LCD interface and enhances learner comprehension by providing immediate feedback.

Discussion: The LCD interface successfully bridges the gap between abstract Boolean theory and practical observation. Students can visualize how input changes affect outputs dynamically, which is not possible with LED-only displays.

4.3. Microcontroller Performance Verification

The ATmega328P was evaluated for its role in reading switch inputs, simulating logic operations, and updating the LCD display.

Observed outcomes include:

1. Accurate reading of debounced toggle switch inputs,
2. Correct simulation of all logic gates,
3. Real-time updating of LCD display without delay,
4. Seamless switching between gates during experimentation.

Discussion: These results demonstrate that the microcontroller provides flexibility and intelligent control, enabling both hardware verification and enhanced educational interaction.

4.4. Educational Assessment

A formative classroom trial was conducted with undergraduate students to assess the trainer's pedagogical effectiveness. Feedback indicated:

1. Students found the LCD display helped visualize logic operations clearly,
2. Switching between gates facilitated rapid experimentation and reinforced learning,
3. Interaction with the trainer improved comprehension of Boolean operations compared to LED-only systems,
4. Hands-on experience strengthened the connection between theory and practical outcomes.

Discussion: These findings support the constructivist learning theory referenced in the methodology. Active engagement with the trainer improves understanding of digital logic, while the hybrid design addresses common laboratory limitations in resource-constrained environments.

4.5. Overall System Performance

The hybrid architecture, combining discrete logic ICs with a programmable microcontroller and LCD interface, was evaluated as reliable and effective. Functional verification confirmed 100% accuracy across all gate types, while LCD feedback provided clear real-time visualization. Educational trials further demonstrated the system's effectiveness in reinforcing student comprehension and engagement.

The results validate the methodology, demonstrating that the proposed digital logic trainer achieves its design objectives of accurate functionality, flexible operation, and pedagogical effectiveness.

5. Conclusion

This work presented the design, implementation, and evaluation of a hybrid digital logic trainer incorporating both discrete 74HC-series ICs and a microcontroller-driven LCD interface. Functional verification confirmed that all implemented logic gates (AND, OR, NOT, XOR, NAND, NOR, XNOR) operated with 100% accuracy according to their canonical truth tables.

The ATmega328P microcontroller effectively handled input scanning, logic simulation, and real-time LCD updates, enhancing flexibility and usability. Educational assessment demonstrated that the trainer improves student comprehension and engagement compared to conventional LED-only trainers. The integration of real-time visual feedback and mini truth tables facilitated a clear understanding of Boolean operations and logic gate behavior, validating the pedagogical objectives of the system. Overall, the proposed methodology proved effective in producing a reliable and educationally beneficial digital logic trainer suitable for undergraduate laboratories.

Despite the successful implementation, several limitations were observed:

1. The LCD display is limited in size (3.5 inches), which constrains the amount of information that can be displayed at once. Larger or higher-resolution displays could improve clarity.
2. The trainer currently focuses on combinational logic only. Sequential logic, flip-flops, counters, and memory elements are not included.
3. The prototype relies on manual toggle switches for inputs. While adequate for small-scale experiments, automated input generation or a GUI interface could enhance usability.
4. The formative educational assessment involved a limited number of students; a larger sample would provide more robust validation of pedagogical effectiveness.

Future enhancements to the digital logic trainer may include:

1. Extending the system to incorporate sequential circuits such as flip-flops, counters, and registers, enabling a more comprehensive digital electronics laboratory tool.
2. Integrating a higher-resolution or touch-enabled LCD to display more detailed truth tables, explanations, or graphical representations of logic states.
3. Implementing automated input sequences via software or PC interface to reduce manual effort and allow rapid testing of complex logic operations.
4. Developing a modular design that allows easy expansion of gate types and circuit complexity without redesigning the hardware.
5. Conducting extensive educational studies across multiple institutions to quantitatively evaluate learning outcomes and long-term comprehension benefits.

In conclusion, this work establishes a reliable, flexible, and pedagogically effective digital logic trainer. The proposed improvements and future directions aim to extend its functionality and enhance its utility as a modern educational tool in digital electronics laboratories.

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Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

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