AtomPlay: Design and Experimental Characterization of a Tangible Electronic Interface for Learning Electron Configuration

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ABSTRACT

Electron configuration requires students to coordinate atomic number, total electron count, and the distribution of electrons among energy levels, yet most educational resources represent electrons symbolically through cards, printed boards, or digital selections. This work presents the design and experimental characterization of AtomPlay, a low-cost tangible electronic interface in which each electron is represented by a physical pushbutton and the resulting occupancy is measured electrically rather than entered as a symbolic selection. The prototype integrates 118 pushbuttons distributed across seven energy-level banks, seven resistive counting channels, a 10-bit analog-to-digital converter, and eight OLED displays controlled by a microcontroller. A transfer model for the resistive counting topology was derived and compared with bench-measured threshold intervals from occupancy states up to 32 simultaneous inputs. With the nominal resistance ratio r = 4.7, the model reproduced the measured midpoints with a mean absolute error of 5.0 ADC counts; least-squares fitting yielded an effective ratio of r = 4.83 and an RMSE of 0.74 counts. Within the calibration ranges, the observed dispersion averaged 1.97 counts and reached 4 counts in the worst case. Analysis of adjacent-count separation showed that the highest-occupancy channels approach the discrimination limit: at k = 32 the nominal design provides a conservative margin of approximately 0.9 relative to the worst-case dispersion. Maximizing the modeled adjacent-state separation yields the closed-form sizing rule r = kmax, which predicts an increase in this margin to approximately 2.0 for a 32-input channel and a practical upper bound on the order of 64 simultaneous inputs per channel for a 10-bit converter under the measured dispersion; the optimized resistance ratio was not physically tested in the present study. AtomPlay therefore contributes both an educational artifact for chemistry and a generalizable low-cost instrumentation strategy for tangible interfaces that count multiple discrete simultaneous inputs through few analog channels. Learning and affective outcomes were not evaluated in this study.

Keywords: electron configuration, tangible interface, educational instrumentation, resistive sensing, microcontroller.

INTRODUCTION

Upper-secondary chemistry relies on entities and models that are difficult to transfer from symbolic representation to direct manipulation. Atomic structure is a clear example: energy levels and electron distributions are commonly taught through notation, diagrams, and filling rules, although later chemistry topics depend on understanding the relationships represented by those symbols.

Electron configuration requires the learner to coordinate three quantities at the same time: the atomic number that identifies an element, the total number of electrons in a neutral atom, and the distribution of that total among shells with different capacities. The difficulty is therefore not limited to remembering a filling sequence. It also involves understanding why the partial occupancies must remain consistent with the atomic

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number.

Game-based approaches have been used to reduce the distance between abstract chemistry content and student action. Systematic and meta-analytic evidence reports favorable effects of game-based learning on motivation and conceptual understanding, although effect magnitude varies among contexts [1], [13], [15]. Chemistry-specific implementations range from periodic-table games and digital tournaments to tools focused directly on electron configuration [5]-[8], [10]. Reviews of the field nevertheless show that cards, printed boards, and screen-based interaction remain dominant formats [2], [3]. In those formats, the electron continues to be represented primarily as a symbol that is selected, drawn, or placed.

A parallel line of work has incorporated low-cost microcontrollers into chemistry education, mainly for data acquisition and laboratory automation [9], [12]. These systems demonstrate the accessibility of embedded instrumentation but generally measure physical variables generated by an experiment. A different design problem emerges when instrumentation is used to measure a representation constructed by the learner. If one physical control corresponds to one electron and one bank corresponds to one energy level, the interface must count many simultaneous discrete inputs while preserving a low component count and a limited number of analog channels.

That requirement transforms an educational design problem into an instrumentation problem. For a bank containing up to 32 simultaneous inputs, adjacent occupancy states must remain electrically distinguishable despite component tolerance, ADC resolution, and measurement dispersion. The reliability of the counting topology is therefore part of the scientific contribution rather than an implementation detail.

The objective of this work was to design and experimentally characterize AtomPlay, a tangible microcontroller-based interface that physically represents electron occupancy by energy level. The study describes the hardware architecture and embedded logic, derives the transfer function of the resistive counting array, compares the model with bench measurements, determines the discrimination limit, and derives a channel-sizing rule that improves that limit. Educational and anxiety-aware design decisions are retained as secondary design considerations. No claims of improved learning or reduced anxiety are made because classroom outcomes were outside the scope of the present characterization.

RELATED WORK AND RESEARCH GAP

Recent electron-configuration resources illustrate the prevailing symbolic interaction paradigm. ChemisTree uses an interactive tree structure, ELQUAN combines a board-based approach with electron configuration and quantum numbers, and E-CONFIG Cards uses cards to support orbital filling [7], [8], [10]. These approaches address the same conceptual domain as AtomPlay, but the learner manipulates a symbolic representation rather than a measured physical occupancy.

At the same time, microcontroller-based chemistry education has demonstrated that low-cost embedded systems can support laboratory learning and mixed virtual-physical environments [9], [12]. AtomPlay connects these two lines of work by using embedded instrumentation not to acquire an external experimental variable, but to quantify a conceptual representation physically constructed by the learner. Unlike card, board, or screen-based approaches in which an electron is selected or placed symbolically, each electron in AtomPlay is embodied as a discrete physical input and the simultaneous occupancy of each level is estimated electrically through a shared analog channel. The research gap addressed here is therefore the lack of a characterized tangible interface in which discrete conceptual units are mapped one-to-one to physical controls and measured through a compact analog counting architecture.

METHODOLOGY

Design context and development process

Development was carried out between September 2025 and January 2026 at an upper-secondary

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technological school in Chihuahua, Mexico. The complete design-build-test-correction cycle was documented in an institutional logbook containing 36 dated and signed entries. The present study concerns the engineering development and bench characterization of the device; no human participants were enrolled and no student outcome data were collected.

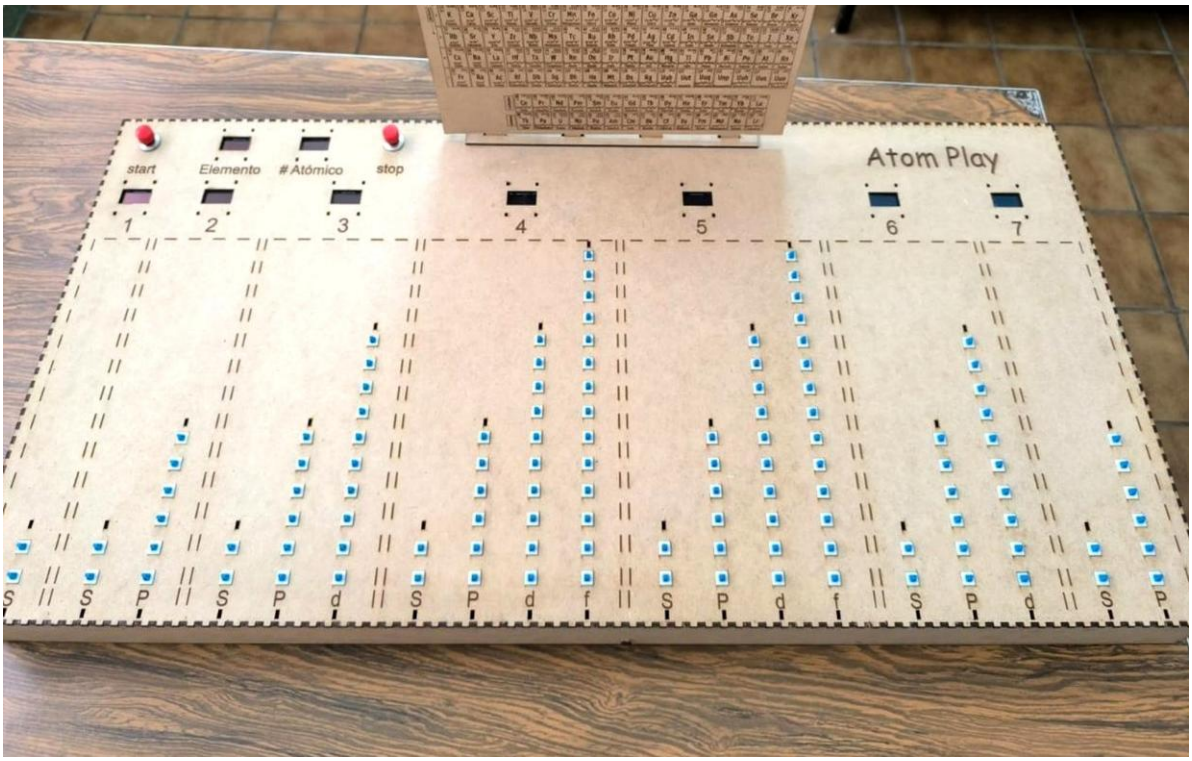


Figure 1: Top view of the AtomPlay prototype. The laser-cut medium-density fiberboard panel integrates pushbutton banks organized by energy level, OLED windows, start and validation controls, and a periodic-table reference support. The Spanish panel labels were digitally replaced by their English equivalents for publication readability; no physical components were altered.

System architecture

AtomPlay is organized into five functional blocks (Figure 2). The input stage contains seven pushbutton banks, one for each energy level, with 118 electron pushbuttons in total plus two control pushbuttons. Each bank is connected to one resistive divider and each divider to one analog input of an Arduino Mega microcontroller. The output stage comprises eight SSD1306 128 × 64 pixel OLED displays managed through a TCA9548A I²C multiplexer.

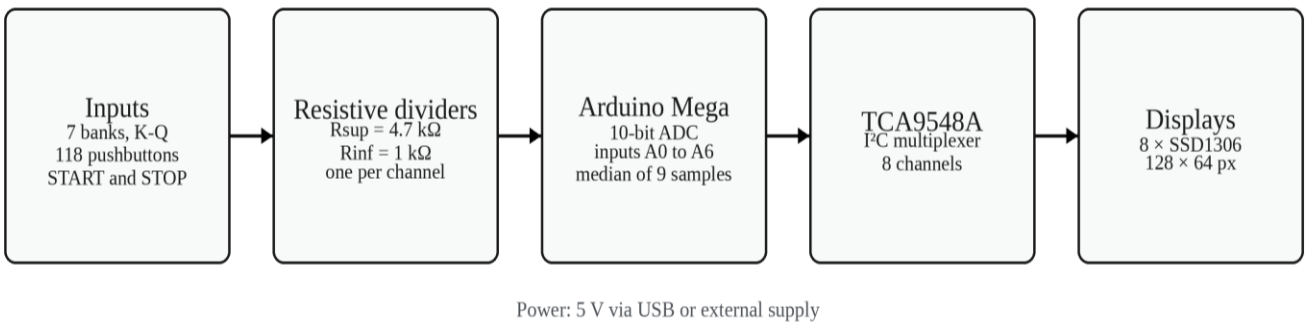


Figure 2: Functional block diagram of AtomPlay. Seven analog counting channels are resolved by the microcontroller using the median of nine consecutive samples per channel.

The central display shows the selected chemical symbol, its atomic number, and the accumulated number of entered electrons. The available set contains 44 representative-group species with atomic numbers from 1 to

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88. Synthetic elements from periods six and seven were excluded because they were not required for the intended upper-secondary learning context.

Table 1: Correspondence among analog channel, energy level, maximum occupancy, associated display, and nominal resistance ratio.

Analog channel	**Energy level**	**Maximum capacity (electrons)**	**Display**	**Nominal resistance ratio, r**
A0	K	2	1	4.7
A1	L	8	2	4.7
A2	M	18	3	4.7
A3	N	32	4	4.7
A4	O	32	5	4.7
A5	P	18	6	4.7
A6	Q	8	7	4.7

Resistive counting principle

Each pushbutton in a bank connects the 5 V supply to the sensing node through an upper resistor, Rsup = 4.7 kΩ nominal, with 5% tolerance. All pushbuttons in the same bank share one lower resistor, Rinf = 1 kΩ nominal, also with 5% tolerance, connected to ground. When k pushbuttons are actuated simultaneously, the k upper resistors are placed in parallel, producing an equivalent upper resistance Rsup/k. During development, the resistance values used in the channels were checked to remain consistent with their nominal values and stated tolerance before the corresponding response thresholds were incorporated into the counting algorithm.

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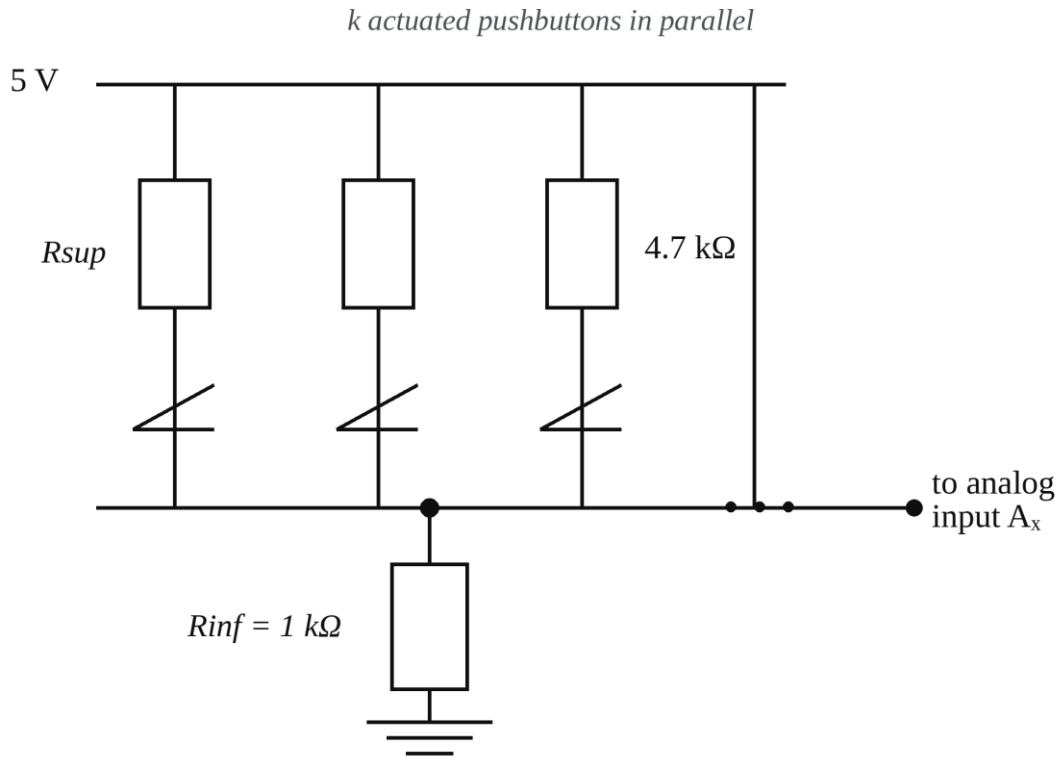


Figure 3: Resistive-divider topology for one channel. The k actuated pushbuttons contribute k equal resistors in parallel between the 5 V supply and the analog sensing node.

The sensing-node voltage is therefore

$$V_x = V_{ref} \cdot R_{inf} / (R_{sup}/k + R_{inf}) \quad (1)$$

For a 10-bit ADC with maximum code Nmax = 1023, the ideal digital reading becomes

$$N(k) = N_{max} \cdot k / (r + k), \quad \text{where } r = R_{sup}/R_{inf}. \quad (2)$$

Equation (2) defines the transfer characteristic of the counting system. Its hyperbolic form means that the separation between consecutive occupancy states decreases as k increases. For adjacent states, the separation can be approximated by

$$\Delta(k) = N(k) - N(k-1) \approx N_{max} \cdot r / (r + k)^2. \quad (3)$$

Embedded operating logic

The control program implements the state machine shown in Figure 4. In the initial state all displays present the resource title. While the START control is held, the system samples elements randomly from the available set and updates the central display every 120 ms. Releasing START fixes the selected element and its atomic number, which defines the target for the current round.

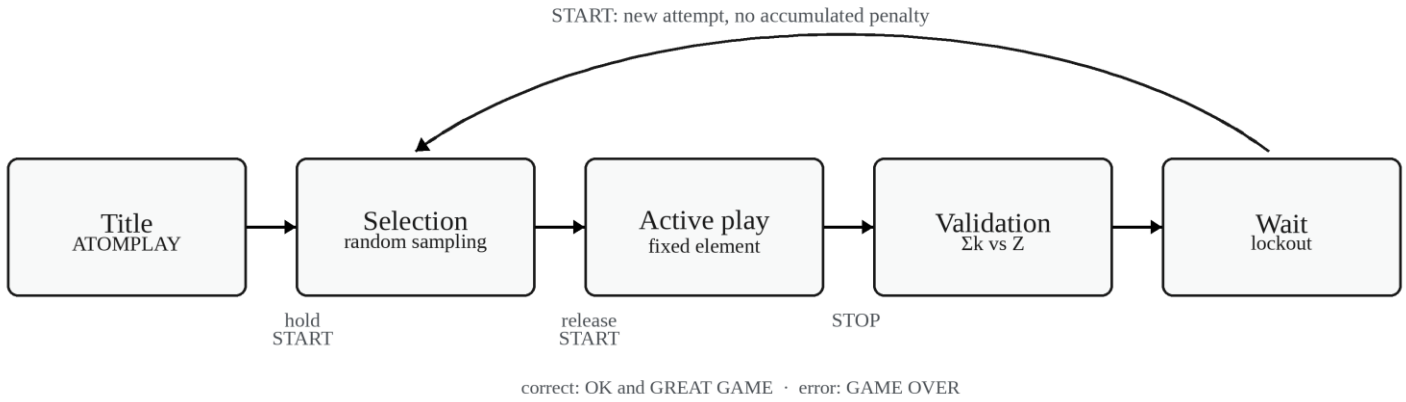


Figure 4: Embedded state machine. Returning from the waiting state starts a new attempt without accumulated penalties or a limit on retries.

During active play, each energy-level display presents its channel count and the central display updates the total in real time. When the validation control is actuated, the program compares the sum of all channel counts with the fixed atomic number and displays the result. Each analog channel is read using the median of nine samples separated by 200 μs to suppress impulsive noise. The complete main-loop cycle is executed every 120 ms. Because the current validation criterion uses only the total electron count, it does not independently verify whether the electrons have been distributed among energy levels according to the reference configuration; this design trade-off is addressed in the Discussion.

Experimental characterization

Bench characterization recorded minimum and maximum ADC readings for occupancy states from k = 1 to k = 32. Characterization was performed as part of an iterative, channel-by-channel calibration process during prototype development: each channel was adjusted experimentally in sequence until its occupancy states could be associated with usable decision ranges under the operating conditions of the prototype. The resistance values used for the channels were checked against their nominal values and stated tolerance before the thresholds were established. The resulting measurements were used to define occupancy intervals and decision boundaries as midpoints between consecutive ranges. The midpoint of each measured interval was compared with Equation (2) using both the nominal resistance ratio and an effective ratio estimated by least-squares fitting over the 32 occupancy states. Measurement dispersion was quantified as the width of the minimum-to-maximum interval for each k. Because this procedure was an engineering calibration process rather than a prespecified repeatability experiment, a fixed number of independent trials per occupancy state was not recorded. Consequently, no trial count, repeatability coefficient, or trial-based standard deviation is reported. The calibration was conducted under indoor bench conditions; temperature and humidity were not systematically varied or recorded as experimental factors, so their independent influence on counting accuracy was not quantified in the present study.

To evaluate count separability, a discrimination margin M(k) was defined as the modeled adjacent-state separation Δ(k) divided by the worst measured dispersion Dmax = 4 ADC counts:

$$M(k) = \Delta(k) / D_{max}. \quad (4)$$

A value M = 1 indicates that the modeled separation equals the worst observed measurement span; values below 1 indicate overlap risk under that conservative criterion. Equation (3) was then used to identify a resistance-ratio rule predicted to improve the critical high-occupancy channels. Experimental verification of the optimized resistance ratio was not part of the present prototype characterization.

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Human-centered educational design considerations

Five design decisions were retained to address known sources of chemistry- and assessment-related anxiety [4], [14]. These are properties of the artifact, not evidence of an affective effect. The device provides local feedback, allows unlimited retries without accumulated penalties, imposes no timer, externalizes the running electron count, and leaves interaction pace under user control. These decisions are reported because they affect the operating logic and intended classroom use; their psychological effect requires separate empirical evaluation.

Table 2: Human-centered design criteria implemented in AtomPlay. These criteria describe artifact properties and intended mechanisms; they are not evidence of reduced anxiety.

Design criterion	Verifiable implementation	Intended design rationale
Local feedback	The result is shown only on the device display; no teacher intervention is required for validation.	Avoids making an incorrect response public by design.
Zero accumulated penalty	After an incorrect result, START begins another attempt; retries are unlimited.	Supports repeated practice without a cumulative failure cost.
No time pressure	The program contains no countdown timer; an earlier timer concept was discarded during development.	Removes device-imposed urgency.
Externalized counting load	Partial counts and the running total are displayed in real time.	Avoids requiring the learner to retain the running total in working memory.
User-controlled pace	Progress depends on pushbutton actuation; the system imposes no sequence or cadence.	Keeps the interaction pace under user control.

RESULTS

Transfer characteristic and model fit

Figure 5 compares the measured threshold midpoints and minimum-to-maximum intervals with the theoretical transfer characteristic evaluated at the nominal and fitted resistance ratios. The plotted intervals correspond to the ranges retained during the iterative calibration process and should not be interpreted as confidence intervals derived from a fixed number of replicate trials. The nominal model, $r = 4.7$, reproduced the measured midpoints with a mean absolute error of 5.0 ADC counts, equivalent to 0.80% of the measured value, and a maximum absolute error of 7.6 counts. Least-squares fitting yielded an effective ratio $r = 4.83$ and an RMSE of 0.74 counts. The 2.8% difference from the nominal ratio is compatible with the stated resistor tolerance and aggregate loading effects at the ADC input node under the calibration conditions. Average measured dispersion was 1.97 counts and the worst observed span was 4 counts.

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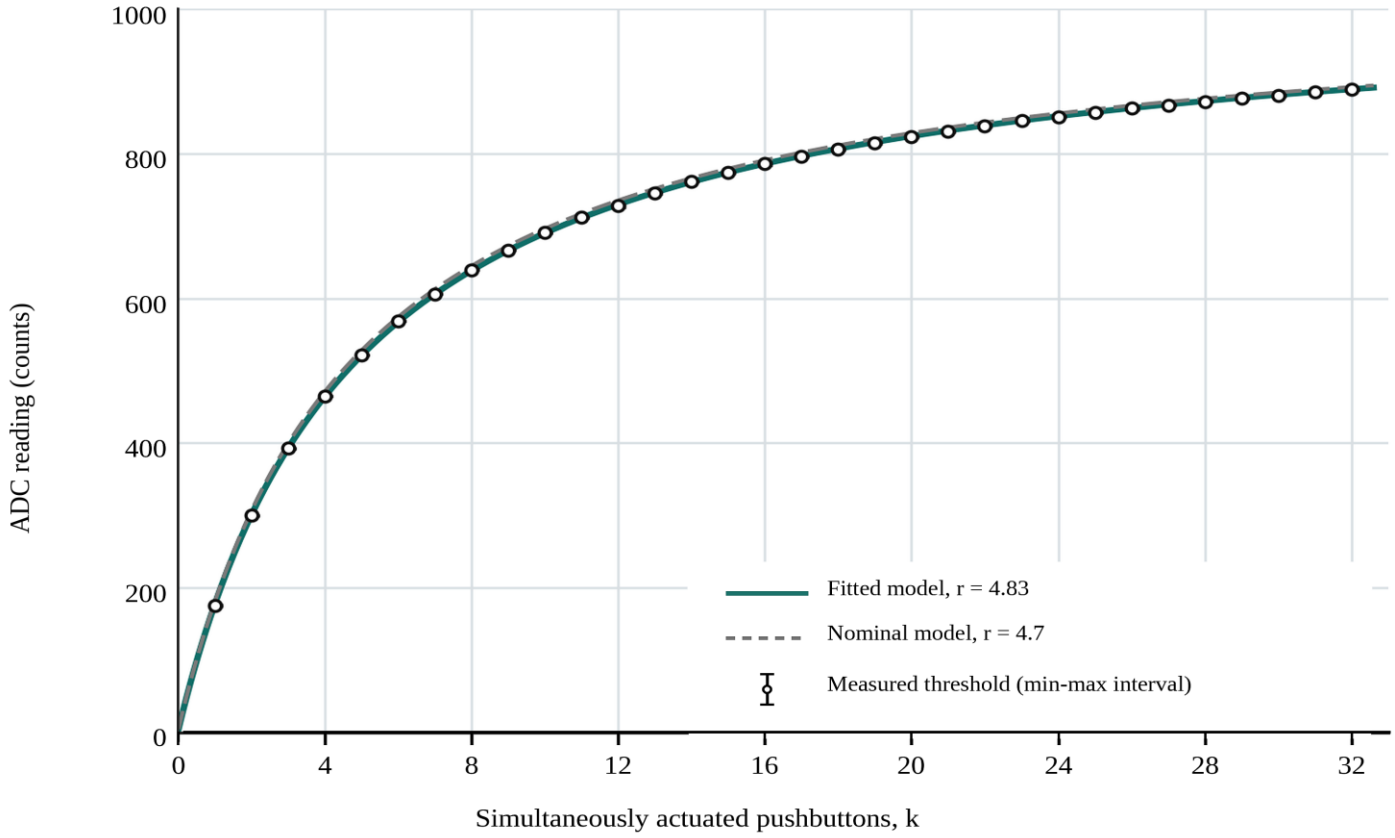


Figure 5: Transfer characteristic of the counting system. Markers represent measured interval midpoints, error bars represent minimum-to-maximum measured ranges, and curves show the nominal and fitted models. The original plotted measurements and curves were preserved while labels were reconstructed in English.

Table 3: Measured thresholds and nominal-model values for selected occupancy states. All values are 10-bit ADC counts.

k	Measured minimum	Measured maximum	Midpoint	Model (r = 4.7)	Difference
1	174	176	175.0	179.5	−4.5
2	299	300	299.5	305.4	−5.9
4	464	464	464.0	470.3	−6.3
8	639	640	639.5	644.4	−4.9
12	726	729	727.5	735.1	−7.6
16	784	788	786.0	790.7	−4.7
18	805	807	806.0	811.2	−5.2
24	850	852	851.0	855.5	−4.5
28	871	873	872.0	876.0	−4.0
32	887	890	888.5	892.0	−3.5

Discrimination limit and channel-sizing rule

The hyperbolic response compresses adjacent states as occupancy increases. Using Equation (3), r = 4.7, k = 32, and Nmax = 1023 gives an adjacent-state separation of approximately 3.6 ADC counts. Relative to the

worst measured dispersion of 4 counts, the resulting discrimination margin is $M(32) \approx 0.9$. Thus, the two 32-input channels operate slightly below the conservative $M = 1$ criterion at their maximum occupancy, even though the prototype remained operational during the recorded bench tests.

For a fixed maximum occupancy kmax, Equation (3) can be maximized with respect to r. The derivative of the factor $r/(r + kmax)^2$ is proportional to $(kmax - r)/(r + kmax)^3$, so the maximum adjacent-state separation occurs when r = kmax. The resulting closed-form sizing rule is

$$r_{opt} = k_{max}. \quad (5)$$

Under this condition, $\Delta(kmax) \approx Nmax/(4kmax)$. For kmax = 32, the predicted adjacent-state separation is approximately 8.0 counts, giving $M \approx 2.0$ under the same 4-count worst-case dispersion. If $M \geq 1$ is used as the minimum conservative separation criterion and the measured Dmax = 4 counts is retained, Equation (5) gives $kmax \lesssim Nmax/(4Dmax) \approx 64$. These values are analytical predictions based on the measured dispersion and 10-bit ADC resolution. The optimized r = kmax network was not physically implemented and directly characterized in this study; therefore, the predicted improvement from approximately 0.9 to 2.0 requires experimental verification in a subsequent hardware iteration. The estimate should also be revalidated when component tolerances, supply conditions, ADC hardware, wiring topology, or environmental conditions change.

Prototype operation

The prototype completed the full state sequence consistently during iterative development and the functional verification documented in the project logbook. Random element selection, fixation of the element after START release, real-time update of level counts and total occupancy, and validation were executed without external intervention. The 120 ms update cycle produced immediate visual response during manipulation. In addition to bench development, AtomPlay was operated as a working demonstration at a local science and technology event at CETis No. 86 and during the 2025 National Prototype Contest, in which the project advanced from the local stage to the state stage. No functional failures were observed during these presentations. These observations provide qualitative evidence of operational robustness under repeated use; however, they are not treated as a formal repeatability experiment because the number and conditions of individual runs were not recorded as a controlled data series.

Recorded incidents were mechanical rather than logical: deficient solder joints in the pushbutton banks and one failed display were corrected by component replacement and subsequent verification. With 118 pushbutton connections, assembly quality is therefore a practical replication constraint and motivates a future printed-circuit implementation.

DISCUSSION

AtomPlay addresses the same chemistry content as recent electron-configuration games but changes the nature of the interaction. Existing resources such as ChemisTree, ELQUAN, and E-CONFIG Cards use symbolic selection or placement [7], [8], [10], whereas AtomPlay establishes a measurable one-to-one correspondence between a conceptual unit and a physical action. The distinction is important because it moves part of the educational-design problem into instrumentation: the device must reliably infer the number of simultaneously actuated discrete controls from a small number of analog channels.

The engineering results extend beyond the specific chemistry application. Equation (2) characterizes the resistive counting topology, while Equations (3)-(5) expose its principal limitation and provide a sizing rule. The nominal 4.7:1 design is adequate over much of the range but compresses high-occupancy states until the predicted separation becomes comparable to the measured dispersion. Selecting r according to the maximum channel occupancy increases endpoint separation without requiring one digital input per pushbutton. This approach can be transferred to other low-cost tangible interfaces in which many equivalent discrete inputs must be counted simultaneously. The fitted effective ratio r = 4.83 is also relevant for replication. A model based only on nominal resistor values introduces a small systematic offset, whereas fitting the effective ratio

reduces RMSE to less than one ADC count. The resistance values used in the prototype were checked against their nominal values and stated tolerance before threshold definition, and the subsequent calibration captures aggregate component and input-node effects under the bench conditions used in this study.

Temperature and humidity were not systematically varied; therefore, the present results should not be interpreted as an environmental-robustness characterization. For replication, empirical calibration should be repeated after assembly and whenever the resistor network, supply, ADC hardware, wiring, or operating environment is materially changed. From an educational perspective, the interface can support introduction, guided practice, or formative assessment. Before formal instruction, it can be used to connect atomic number with a physical total; after instruction, automatic validation can support repeated practice without continuous teacher intervention. In a future classroom implementation, the device could also record the number of attempts and the pattern of level-by-level errors once the validation logic is extended. These are intended uses rather than demonstrated learning effects, because the present study did not include a classroom comparison.

The current validation logic also introduces a specific pedagogical limitation. Validation is based on the equality between the total number of actuated electron controls and the selected atomic number. Consequently, a learner could distribute electrons incorrectly among energy levels yet still obtain a correct result if the total sum equals Z. This simplification reduces embedded complexity but weakens configuration-specific feedback. As an immediate future improvement, the firmware should store the expected occupancy vector for the selected element and compare the seven measured level occupancies with that reference, allowing the interface to distinguish a correct total from a correct distribution. This modification has not been implemented or experimentally tested in the present study and is therefore stated only as future work.

The anxiety-aware decisions follow the same distinction between design rationale and outcome evidence. Chemistry anxiety has been associated with performance, and evaluation, public error, and time pressure have been reported as relevant sources of anxiety [4], [14]. AtomPlay deliberately avoids a timer, public scoring, accumulated penalties, and externally imposed pacing. These properties justify describing the system as anxiety-aware by design, but not as an intervention proven to reduce anxiety.

The principal research limitation is the absence of learner-level validation. A subsequent classroom study should evaluate AtomPlay using a pretest-posttest design focused on electron-configuration knowledge and, when feasible, a comparison with conventional written or digital practice. The primary educational outcome should be change in conceptual accuracy; secondary outcomes may include recurrent error patterns, number of attempts, task-completion time if logging is implemented, and student perceptions of usability. If the anxiety-aware design is evaluated, a validated chemistry-anxiety scale may be incorporated, with optional non-invasive physiological measures such as heart-rate variability or electrodermal activity. Because the intended population includes minors, such a study would require the corresponding ethical approval, institutional authorization, guardian consent, and student assent [11]. A second limitation is that the current hardware relies on extensive point-to-point soldering; a PCB implementation would improve manufacturing repeatability.

CONCLUSION

AtomPlay was developed and characterized as a low-cost tangible electronic interface for learning electron configuration. The device maps each electron to a physical pushbutton and resolves energy-level occupancy through resistive analog measurement, allowing an abstract symbolic operation to be represented as a measurable physical configuration. Experimental characterization showed that the nominal hyperbolic transfer model reproduced measured thresholds with a mean absolute error of 5.0 ADC counts. Fitting the effective resistance ratio to r = 4.83 reduced RMSE to 0.74 counts. Discrimination analysis identified a design limitation at high occupancy: the nominal 32-input channels provide a conservative margin of approximately 0.9 relative to the worst measured dispersion. The derived rule ropt = kmax predicts an increase in this margin to approximately 2.0 for a 32-input channel and gives an architecture-level upper

bound on the order of 64 inputs per channel for the measured dispersion and a 10-bit ADC. The optimized configuration was not physically tested in this study, so the predicted margin improvement remains to be verified experimentally.

The contribution of the work is therefore twofold. First, it provides a functional educational instrument that makes electron occupancy physically manipulable. Second, it provides a transferable characterization and sizing method for low-cost tangible interfaces that count multiple simultaneous discrete inputs through analog channels. The prototype also demonstrated stable functional operation during development and public presentations, although these demonstrations were not designed as a formal repeatability experiment. Claims regarding learning gains or anxiety reduction are intentionally reserved for future classroom validation. Immediate future work should experimentally verify the optimized resistance-ratio configuration and extend firmware validation from total electron count to the complete energy-level distribution vector.

DECLARATIONS

Ethics statement

This study reports engineering development and bench characterization only. No human participants or animals were involved, and no learner-level data were collected; therefore, human-subject or animal ethical approval was not required for the work reported here.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The bench measurements supporting the findings reported in this article are available from the corresponding author upon reasonable request. Control code and fabrication files may be deposited in an open repository in a future replication package.

Declaration of generative AI in scientific writing

During preparation of this manuscript, the authors used a generative AI conversational assistant to support language editing, manuscript organization, and readability. The authors reviewed and edited the resulting text as needed and take full responsibility for the content of the publication. Prototype conception, experimental measurements, analysis, interpretation, and scientific decisions remain the responsibility of the authors.

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