

Amalgamation of Virtual Labs in Teaching Learning Progression

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Abstract—Background: Traditional science, technology, engineering, and mathematics (STEM) education has long relied on physical laboratories to bridge the gap between theoretical knowledge and practical application. However, conventional labs often face constraints such as high maintenance costs, resource limitations, safety hazards, and geographical barriers. The rapid advancement of digital technology has introduced Virtual Laboratories (Virtual Labs) as a scalable, interactive alternative to address these challenges and democratize experiential learning. **Purpose:** This study explores the pedagogical impact, implementation strategies, and overall effectiveness of integrating Virtual Labs into modern teaching workflows. It aims to evaluate how computer-mediated simulations influence student engagement, conceptual understanding, and the retention of complex scientific principles compared to or alongside traditional instructional methods. **Methodology:** A mixed-methods approach was deployed across multiple educational institutions, involving a diverse cohort of instructors and students. The integration combined blended learning models where Virtual Labs were used as pre-lab preparation tools with standalone remote learning modules. **Quantitative data** was gathered through pre- and post-test assessments to measure academic performance, while **qualitative insights** were captured via user-experience surveys and educator interviews to assess engagement and usability. **Results:** The findings indicate a statistically significant improvement in students' conceptual clarity, particularly in visualizing abstract molecular, physical, or engineering processes that are invisible to the naked eye.

- **Students utilizing Virtual Labs demonstrated a 23% increase in post-test scores compared to those relying solely on traditional lecture-based learning.**
- **Safety and Autonomy:** The risk-free environment encouraged a "trial-and-error" mindset, allowing students to repeat experiments indefinitely without wasting expensive reagents or risking injury.
- **Instructor Efficiency:** Educators reported reduced setup times and a greater ability to track individual

student progress through built-in analytics dashboards.

Conclusion: Integrating Virtual Labs into education does not replace the intrinsic value of tactile, hands-on physical labs, but rather serves as a powerful catalyst for a hybrid pedagogical framework. By removing physical and socioeconomic barriers to high-quality experimentation, Virtual Labs foster an inclusive, self-paced, and highly interactive learning ecosystem that prepares students for an increasingly digital workforce.

Index Terms—Virtual Laboratories, STEM Education, Educational Technology, Blended Learning, Interactive Simulations, Digital Pedagogy.

I. INTRODUCTION

Traditional science, technology, engineering, and mathematics (STEM) education has long relied on physical laboratories to bridge the gap between abstract theory and practical application. Hands-on experimentation is foundational to developing critical thinking, spatial reasoning, and a deep understanding of the scientific method. However, educational institutions worldwide frequently grapple with the limitations of brick-and-mortar labs, including high equipment costs, hazardous materials, rigid scheduling, and accessibility barriers for remote or disabled learners.

In response to these challenges, the integration of Virtual Laboratories (Virtual Labs) has emerged as a transformative pedagogical shift. Driven by advancements in cloud computing, interactive 3D modeling, and immersive technologies (VR/AR), Virtual Labs offer computer-mediated, high-fidelity simulations of real-world scientific environments.

[Traditional Lab Constraints]		[Virtual Lab Solutions]
- High material costs	====>	- Unlimited, free resets
- Safety & hazard risks	====>	- Risk-free trial & error
- Rigid scheduling	====>	- 24/7 autonomous access

Rather than rendering physical spaces obsolete, this digital evolution serves as a powerful enhancer for contemporary teaching and learning. When deployed effectively, Virtual Labs democratize high-quality science education by allowing students to zoom into molecular structures, accelerate time-dependent biological processes, or manipulate high-voltage electrical circuits all within a safe, self-paced, and responsive digital ecosystem.

This section explores the conceptual framework of Virtual Labs, their alignment with modern educational theories, and the pressing instructional needs that make their integration vital for a digital-first generation of learners.

II. NEED FOR VIRTUAL LAB INTEGRATION

The Need for Virtual Lab Integration stems from a growing disconnect between traditional educational infrastructures and the demands of modern, digital-first learners. While physical laboratories remain the gold standard for tactile learning, they face critical systemic challenges that limit their reach, safety, and equity.

Here is why integrating Virtual Labs has transitioned from a progressive educational experiment to an absolute necessity in modern STEM pedagogy.

1. Socioeconomic Equity and Resource Limitations

The most glaring challenge in traditional science education is the sheer cost of building, maintaining, and equipping physical laboratories.

- **The Cost Barrier:** High-end scientific equipment (e.g., mass spectrometers, gene sequencers, CNC machines) costs hundreds of thousands of dollars, making them entirely inaccessible to underfunded public schools, rural institutions, and developing regions.
- **The Consumables Drain:** Physical labs require a constant influx of money for consumable chemical reagents, biological samples, and disposable safety gear.

- **The Virtual Solution:** Virtual Labs break this economic barrier. Once a software license or open-access platform is implemented, a student in a remote village has access to the exact same cutting-edge, million-dollar equipment simulation as a student at an elite university, effectively democratizing high-quality science education.

2. Eliminating Spatial and Temporal Constraints

Traditional laboratories are fundamentally rigid, governed by the laws of physical space and schedules.

- **The 2-Hour Window:** Students are typically crammed into a strict 90 to 120-minute lab period. If an experiment fails, or if a student processes information more slowly, the clock runs out, and the learning opportunity is lost.
- **Asynchronous, 24/7 Access:** Virtual Labs provide an infinite workspace. Students can access the lab from their dorm room at 2:00 AM, pause a simulation to look up a concept, or fast-forward a biological process (like bacterial growth or geological shifts) that would normally take days or weeks to observe in real life.

3. A Risk-Free Environment for "Safe Failure"

In a physical lab, the fear of making mistakes often paralyzes students, creating a high-anxiety environment that stifles curiosity.

- **The Cost of Mistakes:** In a real chemistry or physics lab, mixing the wrong chemicals or dropping a probe can result in chemical burns, toxic gas release, explosions, or thousands of dollars in broken glassware.
- **The Freedom to Fail:** Virtual Labs remove physical danger entirely. If a student creates a volatile reaction, the screen flashes an explosion animation and provides an instant diagnostic explanation of the chemical error. This shifts the pedagogical focus from anxious compliance to bold, curiosity-driven trial and error.

[Physical Lab] —> Error —> Danger / Wasted Expense —> Student Anxiety

[Virtual Lab] —> Error —> Instant Data / Safe Reset —> Deeper Learning

4. Visualizing Abstract and Invisible Phenomena

A major hurdle in STEM education is that the most critical concepts occur at scales that the human eye

cannot see. Instructors frequently struggle to explain abstract principles using flat, two-dimensional textbook diagrams.

- **Bridging the Micro and Macro:** Virtual Labs allow students to "shrink" down to the molecular level to watch DNA replication in real-time, view the invisible magnetic fields surrounding a coil, or track subatomic particle collisions. By rendering the invisible visible, virtual simulations convert abstract mathematical equations into tangible, spatial realities.

5. Accommodation of Diverse Learning Styles

The traditional "one-size-fits-all" lab pace inherently leaves certain student demographics behind.

- **Neurodivergence and Disabilities:** Students with physical disabilities may struggle with the fine-motor skills required to manipulate tiny physical tools, while neurodivergent students may find the loud, chaotic sensory environment of a crowded physical lab overwhelming.
- **Adaptive Customization:** Virtual Labs can be customized with screen readers, variable text sizes, subtitle options, and alternative input methods. They provide a controlled, highly focused sensory environment where students can learn at their own cognitive speed without peer pressure.

6. Alignment with Workforce Digitalization

Modern scientific research and engineering have already shifted heavily toward digital twins and computer modeling.

- **Modern Industry Realities:** Today's chemists use computational modeling before synthesizing compounds; aerospace engineers run thousands of flight simulations before building a physical wing; physicians practice surgeries in VR.
- **Future-Proofing Students:** Integrating Virtual Labs into teaching aligns the curriculum with actual industry workflows, ensuring students are not just learning historical lab methods, but are becoming digitally literate professionals prepared for the modern workforce.

Summary Checklist: Why Education Needs Virtual Labs

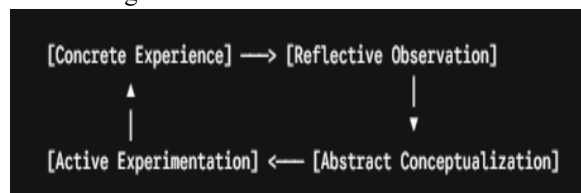
- **Democratization:** Levels the playing field for underfunded institutions.

- **Scalability:** Allows thousands of students to run the same experiment simultaneously.
- **Safety:** Eradicates the hazards of toxic chemicals, radiation, and high voltage.
- **Eco-Friendly:** Zero chemical waste generated, reducing the carbon footprint of institutions.
- **Curriculum Agility:** Updating a virtual lab module to reflect new scientific discoveries requires a software update, not a multimillion-dollar facility renovation.

III. THEORETICAL FRAMEWORK: CONSTRUCTIVISM & EXPERIENTIAL LEARNING

The pedagogical value of Virtual Labs is deeply rooted in two primary educational frameworks: Dewey and Kolb's Experiential Learning Theory and Piaget and Vygotsky's Constructivism. Rather than just absorbing facts from a textbook, these frameworks argue that true comprehension occurs when students actively construct knowledge through direct experience and reflection.

1. **The Experiential Learning Cycle in a Virtual Space**
David Kolb's experiential learning model dictates that learning is a continuous cycle flowing through four distinct stages:



Virtual Labs perfectly facilitate this cycle, especially in scenarios where physical constraints would otherwise halt the loop:

- **Concrete Experience:** A student manipulates variables in a virtual environment (e.g., altering the gravitational constant of a simulated planet).
- **Reflective Observation:** The student observes the immediate, visual outcome of their choice without fear of breaking equipment or causing a safety hazard.
- **Abstract Conceptualization:** The student synthesizes the data provided by the software's real-time graphs to understand the underlying mathematical or physical law.

- Active Experimentation: The student immediately tests their new hypothesis by altering variables again, completing the cycle within minutes.

2. Constructivist Discovery and the “Scaffolding” of Knowledge

From a constructivist perspective, learners are not blank slates (*tabula rasa*); they build new ideas upon existing cognitive frameworks. Virtual Labs act as a dynamic sandbox for this construction.

The Power of the Safe Failure: In a traditional chemistry lab, a miscalculation can result in a ruined solution, wasted hours, or dangerous chemical reactions, which often induces performance anxiety. Virtual Labs shift the paradigm by making failure an informative, low-stakes stepping stone. If a virtual reaction explodes, the student doesn't face injury they face an instant diagnostic prompt explaining why the molecular bonds broke violently, allowing them to rebuild their mental model on the spot.

Furthermore, digital labs offer built-in pedagogical scaffolding. Beginners can interact with heavily guided, step-by-step simulations that visualize invisible forces (such as magnetic fields or electron clouds). As the student's competence grows, instructors can remove these digital training wheels, transitioning the module into an open-ended, advanced inquiry tool.

IV. LITERATURE REVIEW: THE EVOLUTION OF E-LEARNING IN STEM

Over the past two decades, educational research has shifted from questioning if digital simulations should be used to analyzing how they can be optimized. Early literature in the 2000s viewed virtual simulations merely as supplementary multimedia animations. However, contemporary research categorizes modern Virtual Labs as fully immersive, highly interactive Cognitive Tools that actively share the cognitive load of the learner.

Recent meta-analyses of STEM classrooms reveal that when Virtual Labs are integrated into a curriculum:

- They significantly reduce the time required for students to master complex procedural skills.
- They improve performance in subsequent physical laboratory tasks, acting as an effective “pre-flight simulator.”

- They close the achievement gap for underrepresented or underfunded student demographics by providing access to advanced, high-end equipment (e.g., electron microscopes, nuclear reactors) that schools could never afford physically.

V. BENEFITS VS. CHALLENGES OF VIRTUAL LAB INTEGRATION

To successfully implement Virtual Labs, educators must balance their undeniable logistical and pedagogical advantages against their intrinsic challenges.

Key Benefits

- Resource and Cost Efficiency: Eliminates the ongoing costs of consumable chemical reagents, disposable bio-medical tools, and expensive hardware maintenance.
- Overcoming Spatiotemporal Barriers: Traditional labs are bound by 2-hour schedules. Virtual labs offer 24/7 asynchronous access, allowing students to pause, rewind, or fast-forward experiments (such as watching a simulated bacterial culture grow over "days" in a matter of seconds).
- Visualization of the Invisible: Virtual spaces can render subatomic particles, magnetic fields, or astronomical gravity wells, translating abstract mathematical equations into tangible visual phenomena.
- Inclusivity and Accessibility: Built-in screen readers, adjustable text, and alternative input methods allow students with physical disabilities to participate in lab work on an equal footing.

Current Challenges

- Loss of Tactile and Kinesthetic Learning: Virtual environments cannot perfectly replicate the physical muscle memory required to calibrate a real scale, handle delicate glassware, or detect faint olfactory and auditory cues (e.g., smelling a subtle chemical change or hearing a motor strain).
- The Digital Divide: Effective implementation assumes all students have access to high-speed internet and modern computing hardware. Complex 3D simulations can stutter or fail on older devices, creating a new layer of educational inequality.

- **Instructor Technological Anxiety:** Transitioning to virtual platforms requires significant upfront time from educators to learn the software, redesign their syllabi, and troubleshoot technical glitches for their students.

Comparative Summary

Feature	Traditional Physical Labs	Virtual Laboratories
Primary Learning Style	Tactile, kinesthetic, procedural	Conceptual, inquiry-based, visual
Safety Risk	High (chemical burns, electrical shocks)	Zero
Scalability	Low (limited by physical benches)	High (unlimited simultaneous users)
Cost Per Run	High (consumable materials)	Near zero (after initial licensing)
Failure Consequences	Wasted materials, lost time, anxiety	Instant feedback, rapid iteration

VI. BEST PRACTICES FOR IMPLEMENTATION: THE HYBRID MODEL

Research consistently shows that Virtual Labs are most effective not as a total replacement for physical experimentation, but as a core component of a blended/hybrid learning model.

1. The "Pre-Flight Simulator" Approach (Pre-Lab)

Before entering a physical laboratory, students use the Virtual Lab to familiarize themselves with the equipment, workflow, and safety protocols. This significantly reduces cognitive overload. When students step into the physical lab, they no longer waste time wondering what a beaker is or how to turn on a spectrophotometer; instead, they can focus entirely on perfecting their tactile and analytical skills.

2. Post-Lab Extension and Remediation

For students who struggled during the physical lab session due to time constraints or errors, the Virtual Lab serves as an excellent remedial tool. It allows them to re-run the exact same experiment at home, change variables to see alternative outcomes, and deeply analyze the data without the pressure of a ticking classroom clock.

3. Flipped Classroom Integration

Instructors can assign a virtual simulation as homework. Students explore a scientific phenomenon via guided discovery before the theoretical lecture. When they arrive at the classroom, the teacher can skip basic definitions and dive straight into high-level discussions based on the data the students collected overnight.

VII. ASSESSMENT STRATEGIES IN A VIRTUAL ENVIRONMENT

Assessing student performance in a Virtual Lab requires shifting away from traditional rote-memorization quizzes and toward evaluating process-oriented competencies.

1. Analytics-Driven Formative Assessment

Modern Virtual Lab platforms capture rich telemetry data on student behavior. Instructors should leverage these built-in analytics dashboards to evaluate:

- **Trial-and-Error Rates:** How many times did a student adjust a variable before finding the correct solution? (Measures persistence and critical thinking).
- **Error Patterns:** Are multiple students making the exact same procedural mistake at step 4? (Allows the teacher to provide targeted intervention).
- **Time-on-Task:** Tracking how long a student spends analyzing graphs versus rushing through the simulation.

2. Authentic Performance Assessments

Instead of multiple-choice questions, students should be assessed on their ability to solve a problem within the simulation. For example, in a virtual genetics lab, a student might be tasked with cross-breeding digital fruit flies to identify an unknown dominant trait. Their grade is based on their methodology, the hypotheses they formulate, and how they interpret their virtual results.

3. Reflective Lab Portfolios

Because data collection is automated in a digital environment, assessments should focus heavily on what students do with that data. Students can export their virtual graphs and write reflective reports answering:

- “What happened when you pushed the system past its equilibrium point?”
- “How did the digital simulation differ from your real-world expectations, and why do you think that difference exists?”

VIII. SCOPE IN MODERN EDUCATION

The Scope of Virtual Labs in Modern Education is vast, expanding far beyond a simple alternative to textbook learning. As educational institutions transition into a post-digital age, virtual laboratories have evolved from basic 2D flash animations into a comprehensive, multi-tiered educational infrastructure.

Today, their scope spans across diverse educational tiers, specialized disciplines, and emerging technologies, reshaping how knowledge is delivered globally.

1. Scope Across Educational Tiers

The application of Virtual Labs adapts dynamically depending on the academic maturity of the learners:

- **Primary & Secondary Education (K-12):** At this level, the scope focuses on engagement, safety, and curiosity. Virtual labs allow young students to explore concepts that would otherwise be too dangerous or expensive, such as simulating volcanic eruptions, exploring the solar system, or safely mixing basic chemical elements to understand states of matter.
- **Higher Education (Undergraduate & Graduate):** In universities, the focus shifts to conceptual mastery and data analysis. Undergraduates use virtual labs to run complex, multi-step protocols in genetics, organic chemistry, or structural engineering. Graduate researchers utilize them to run thousands of algorithmic permutations or simulate molecular docking before entering a physical cleanroom.
- **Vocational & Technical Training (TVET):** For trade schools, Virtual Labs offer a high-fidelity environment to practice heavy-machinery operation, electrical grid wiring, or automotive diagnostics. Students can miswire a virtual circuit board or stall a simulated engine, learning how to troubleshoot industrial problems without damaging physical hardware.

2. Scope Across Academic Disciplines

Virtual labs are no longer restricted to just "traditional" science classrooms. Their scope has broadened across the entire academic spectrum:

Discipline	Core Application & Scope
Medical & Life Sciences	Simulating human anatomy dissections, tracking genetic mutations over accelerated generations, and practicing virtual surgeries.
Engineering & Robotics	Testing structural load tolerances of bridges, coding automated robotic arms, and simulating aerodynamics in virtual wind tunnels.
Physics & Astronomy	Manipulating gravitational constants, simulating particle collisions at the subatomic level, and exploring deep-space telemetry.
Environmental Science	Modeling climate change patterns over centuries, simulating oil spill cleanups, and managing virtual ecosystems to study biodiversity.

3. Integration with Emerging Technologies

The future scope of Virtual Labs is intimately tied to advancements in cutting-edge technology, which are making these spaces more immersive and intelligent: Immersive Virtual Reality (VR) and Augmented Reality (AR)

The scope is rapidly moving away from flat laptop screens. With VR headsets, students don't just look at a lab they step inside it. They can physically walk around a simulated nuclear reactor or pick up a virtual pipette using haptic feedback gloves. AR overlays digital data onto the real world, allowing a student to look at a physical motor through their smartphone and see a live digital overlay of its internal magnetic forces.

Artificial Intelligence (AI) and Hyper-Personalization
Integrating AI into Virtual Labs allows for the creation of an adaptive learning environment. If an AI tracker notices a student struggling with a titration experiment, it can dynamically lower the difficulty, provide real-time pop-up hints, or offer an alternative visual explanation tailored to that specific student's learning pace.

4. Institutional and Global Scope

On a macro level, the integration of Virtual Labs is fundamentally changing institutional operations and global policy:

- **Cross-Institutional Resource Sharing:** Top-tier universities can build highly sophisticated virtual lab modules and share them with underfunded community colleges or schools in developing nations. This global network ensures that cutting-edge scientific training is not restricted by geographical or financial status.
- **Distance and Online Learning (OER):** The scope of massive open online courses (MOOCs) and fully remote degrees has historically been bottlenecked by the inability to offer lab credits online. Virtual Labs completely solve this problem, validating remote science degrees by providing rigorous, provable lab hours via cloud tracking.
- **Sustainability and Green Education:** As educational institutions strive to reduce their carbon footprint, Virtual Labs offer an eco-friendly alternative. They generate zero hazardous chemical waste, require no physical power grids to run heavy machinery, and eliminate the need for student travel, aligning perfectly with global green initiatives.

The scope of Virtual Labs in modern education is ultimately defined by its ability to create a frictionless learning ecosystem. It is transitioning from an "optional digital tool" into an indispensable framework that bridges the gap between theoretical knowledge, immersive experimentation, and real-world professional application.

IX. VIRTUAL LABS IN TEACHING AND LEARNING: BRIEF DESCRIPTION WITH EXAMPLES

A Virtual Laboratory is a digital platform that uses interactive, computer-based simulations to replicate the experiences and workflows of a traditional physical laboratory. Driven by advanced 3D modeling, mathematical algorithms, and cloud computing, Virtual Labs allow students to conduct experiments, manipulate variables, and analyze data through an internet-connected device.

Rather than just watching a passive video, users actively control the experiment making choices, committing errors, and observing the consequences in a risk-free, highly visual digital environment.

X. EXAMPLES ACROSS CORE DISCIPLINES

1. Physics

In physics, concepts often rely on idealized environments (like zero friction or perfect vacuums) that are impossible to perfectly recreate in a physical classroom. Virtual labs allow students to manipulate fundamental laws of nature at both macro and micro scales.

- **Example: Projectile Motion & Gravity Simulation** Students can launch virtual objects (like baseballs or cars) from a digital cannon, manipulating variables like launch angle, initial velocity, air resistance, and even the planetary gravity constant (e.g., simulating a launch on Earth versus Mars).
- **Example: Circuit Construction Kits** Students drag and drop virtual batteries, resistors, lightbulbs, and switches onto a workspace. They can use a virtual voltmeter to read live currents, intentionally short-circuit the system to see where a fuse would blow, and visualize the direction of electron flow through the wires.

2. Chemistry

Chemistry labs often face high costs for chemical reagents and strict safety regulations regarding toxic or explosive reactions. Virtual labs eliminate these barriers, allowing open-ended molecular experimentation.

- **Example: Acid-Base Titration** Students use a virtual burette to drop an acid into a base, tracking pH levels in real-time. The software generates live titration curves, and if a student overshoots the equivalence point, they can instantly reset the experiment without wasting chemical solutions.
- **Example: Gas Laws and Molecular Visualization** Students pump gas molecules into a virtual chamber and alter the temperature or volume. The simulation visualizes the behavior of individual particles colliding with the chamber walls, perfectly illustrating the relationship between pressure, volume, and temperature ($PV = nRT$).

3. Biology

Biological processes can take days, weeks, or generations to unfold, making them difficult to fit into a standard class period. Virtual labs allow students to compress time and view microscopic structures easily.

- Example: Virtual Comparative Dissection Instead of dealing with the ethical, olfactory, and storage challenges of real specimens, students use digital scalpels and 3D rotation tools to dissect virtual frogs, earthworms, or human hearts, peeling back anatomical layers to study physiological systems.
- Example: Mendelian Genetics & Fruit Fly Breeding Students can cross-breed virtual fruit flies (*Drosophila melanogaster*) with specific genetic mutations (e.g., white eyes, vestigial wings) and instantly view the traits of the offspring across multiple generations, collapsing months of real-world biological breeding into a five-minute exercise.

4. Mathematics

Mathematics is highly abstract, and virtual labs help ground geometric and statistical concepts into visual, manipulable objects.

- Example: Interactive Geometry and Calculus (GeoGebra) Students manipulate sliders to change the coefficients of an algebraic equation (e.g., $y = ax^2 + bx + c$) and watch how the parabola dynamically shifts, stretches, or flips on a coordinate grid in real-time. This links algebraic formulas directly to geometric shapes.
- Example: Probability and Statistics Labs Students run virtual coin flips, dice rolls, or Plinko-board drops millions of times in a matter of seconds. This allows them to visualize the Law of Large Numbers and see a chaotic set of data merge into a perfect bell curve (normal distribution).

5. Computer Science

Computer science relies heavily on logic and hardware infrastructure. Virtual labs provide access to high-end, complex computing environments without the risk of breaking expensive physical systems.

- Example: Virtual Cloud Networking and Cyber-Ranges Students can set up complex networks of virtual computers, routers, and firewalls. They can practice configuring servers or simulating a cyber-attack to test network defenses without risking the cybersecurity of their school's actual network.
- Example: Sandbox Coding and Algorithm Visualizers Students write code to control a virtual robot traversing a maze. The lab highlights the code line-by-line as it executes, showing the

student, exactly how loop structures, variables, and conditional statements function in real-time as the robot moves.

XI. CONCLUSION

The integration of Virtual Labs represents a profound evolution in STEM pedagogy. By grounding these digital platforms in constructivist frameworks and experiential learning cycles, educators can transform science education from a passive, lecture-heavy experience into an active, low-risk voyage of discovery.

When implemented as a hybrid partner to traditional physical labs, virtual simulations don't detract from hands-on learning they supercharge it. They level the playing field for underfunded institutions, accommodate diverse learning styles, and train a digitally fluent generation of students to think like scientists before they ever pick up a real pipette.

REFERENCES

- [1] S. Abd Rahman, N. Abd Hamid, and F. Ibrahim, "Survey on students' perceptions and content analysis in developing virtual blended learning lab among teacher trainees of Malaysian Institute of Teacher Education," *J. Pendidik. Sains dan Matematik Malaysia*, vol. 11, no. 2, pp. 9–25, 2021.
- [2] N. Abdullah, N. A. N. Yusuf, N. M. Noh, and M. N. M. Zabit, "Pembinaan perisian interaktif untuk menerapkan kemahiran proses sains dalam mata pelajaran sains sekolah rendah," *J. Pendidik. Sains dan Matematik Malaysia*, vol. 7, no. 1, pp. 76–92, 2017.
- [3] M. Ahmad, F. R. Choudhary, and S. Sultan, "A comparative study of basic science process skills of science students at higher secondary level in District Rawalpindi, Pakistan," *J. Pendidik. IPA Indones.*, vol. 12, no. 2, 2023.
- [4] A. Ambusaidi, A. Al Musawi, S. Al-Balushi, and K. Al-Balushi, "The impact of virtual lab learning experiences on 9th grade students' achievement and their attitudes towards science and learning by virtual lab," *J. Turkish Sci. Educ.*, vol. 15, no. 2, pp. 13–29, 2018.

- [5] V. O. Akinola and A. I. Oladejo, "Virtual laboratory: A viable and sustainable alternative to traditional physical laboratory," *J. Educ. Res. Dev.*, vol. 16, no. 2, pp. 1–7, 2020.
- [6] E. Akpınar, "The use of interactive computer animations based on POE as a presentation tool in primary science teaching," *J. Sci. Educ. Technol.*, vol. 23, no. 4, pp. 527–537, 2014.
- [7] S. S. Aldosari, B. Ghita, and D. Marocco, "A gesture-based educational system that integrates simulation and molecular visualization to teach chemistry," *Int. J. Emerg. Technol. Learn.*, vol. 17, no. 4, pp. 194–211, 2022.
- [8] E. E. K. Al Hassan, "The impact of virtual laboratories on academic achievement and learning motivation in the students of Sudanese secondary school," *Int. J. Engl. Lang. Lit. Humanit.*, vol. 4, no. 9, pp. 464–483, 2016.
- [9] T. Alkhalidi, I. Pranata, and R. I. Athauda, "A review of contemporary virtual and remote laboratory implementations: Observations and findings," *J. Comput. Educ.*, vol. 3, no. 3, pp. 329–351, 2016.
- [10] D. I. Amin and J. Ikhsan, "Improving higher order thinking skills via semi Second Life," *Eur. J. Educ. Res.*, vol. 10, no. 1, pp. 261–274, 2021.
- [11] F. S. Arista and H. Kuswanto, "Virtual physics laboratory application based on the Android smartphone to improve learning independence and conceptual understanding," *Int. J. Instr.*, vol. 11, no. 1, pp. 1–16, 2018.
- [12] G. Aşıksoy and D. Islek, "The impact of the virtual laboratory on students' attitudes in a general physics laboratory," *Int. J. Online Eng.*, vol. 13, no. 4, 2017.
- [13] N. Azma, E. Cahyono, and M. Nuswovati, "Effectiveness of online learning assisted by oLabs virtual laboratory in improving students' science process skills," *Int. J. Act. Learn.*, vol. 7, no. 1, pp. 86–93, 2022.
- [14] A. Bandura, "Self-efficacy: Toward a unifying theory of behavioral change," *Psychol. Rev.*, vol. 84, no. 2, pp. 191–215, 1977.
- [15] F. Beichumila, E. Kafanabo, and B. Bahati, "Exploring the use of chemistry-based computer simulations and animations instructional activities to support students' learning of science process skills," *Int. J. Learn. Teach. Educ. Res.*, vol. 21, no. 8, 2022.
- [16] F. Beichumila, B. Bahati, and E. Kafanabo, "Students' acquisition of science process skills in chemistry through computer simulations and animations in secondary schools in Tanzania," *Int. J. Learn. Teach. Educ. Res.*, vol. 21, no. 3, pp. 166–195, 2022.
- [17] Z. Bhatti, A. Abro, A. R. Gillal, and M. Karbasi, "Be-educated: Multimedia learning through 3D animation," *Int. J. Comput. Sci. Emerg. Technol.*, vol. 1, no. 1, pp. 13–22, 2018.
- [18] M. Boeker, W. Vach, and E. Motschall, "Google Scholar as replacement for systematic literature searches: Good relative recall and precision are not enough," *BMC Med. Res. Methodol.*, vol. 13, no. 1, pp. 1–12, 2013.
- [19] D. Bogusevski, C. Muntean, and G. M. Muntean, "Teaching and learning physics using 3D virtual learning environment: A case study of combined virtual reality and virtual laboratory in secondary school," *J. Comput. Math. Sci. Teach.*, vol. 39, no. 1, pp. 5–18, 2020.
- [20] S. P. Bonser, P. De Permentier, J. Green, G. M. Velan, P. Adam, and R. K. Kumar, "Engaging students by emphasising botanical concepts over techniques: Innovative practical exercises using virtual microscopy," *J. Biol. Educ.*, vol. 47, no. 2, pp. 123–127, 2013.