

Chemar with 3D Animation

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Abstract: *Augmented Reality (AR) is redefining the way chemistry concepts are taught and understood by enabling the visualization of complex structures and reactions in an interactive environment. This paper presents a web-based AR system for chemistry education developed using HTML, CSS, and JavaScript for the user interface and front-end rendering, with Python Flask (app.py) as the backend framework. The system supports real-time visualization of 3D molecular models, laboratory apparatus, and reaction simulations through standard web browsers, eliminating the need for external applications. The frontend handles animations and user interactions, while Flask manages routing, asset delivery, and client-server communication. The proposed approach demonstrates that lightweight web technologies can effectively deliver immersive AR experiences that enhance conceptual clarity, engagement, and accessibility. The solution is well-suited for applications such as virtual laboratories, classroom demonstrations, and self-directed learning modules.*

Keywords: Augmented Reality, Chemistry Education, Flask, Web Technologies, 3D Visualization, HTML, CSS, JavaScript, Python

I. INTRODUCTION

Chemistry education often faces limitations such as restricted access to laboratories, safety concerns, and the inability to clearly visualize molecular-level changes during reactions. ChemAR addresses these gaps through a web-based interactive platform that simulates real chemistry experiments using 3D animations and planned AR (Augmented Reality) integration. The system allows students to observe chemical reactions phase by phase, understand molecular behavior, and interact with the changes that occur during reactions. ChemAR addresses these gaps through a web-based interactive platform that simulates real chemistry experiments using 3D animations and planned AR (Augmented Reality) integration. The system allows students to observe chemical reactions phase by phase, understand molecular behavior, and interact with experiments safely and repeatedly without the need for physical lab equipment.

The platform is designed using modern web technologies like HTML, CSS, JavaScript, Flask (Python), Three.js, and WebGL, enabling real-time rendering of atoms, bonds, particles, and reaction effects such as bubbles, foam, and oxidation. It includes eight curriculum-aligned chemical experiments with features such as play/pause controls, speed adjustment, chemical equations, progress indicators, and educational text overlays.

The primary motivation behind ChemAR is to bridge the gap between theoretical learning and practical observation. Students often find it difficult to understand how molecules interact, how bonds form or break, and how visible changes in experiments relate to underlying reactions. By delivering accurate visualizations and modular experiment logic, ChemAR improves conceptual understanding while overcoming lab constraints related to cost, safety, and availability.

The scope of this work includes browser-based simulations that run on both desktop and mobile devices, with plans to extend into AR for immersive visualization. The platform serves students, instructors, and educational institutions seeking an accessible and scalable alternative to conventional practical labs.



II. LITERATURE SURVEY

Recent studies in the field of chemistry education have increasingly highlighted the role of Augmented Reality (AR) and related visualization tools in improving students' conceptual understanding and engagement.

Sánchez et al. (2022) examined various AR frameworks designed for representing and manipulating three-dimensional molecular structures. Their review emphasized that, although AR applications are still not widely adopted in chemistry classrooms, they hold strong potential for improving students' spatial reasoning and structural visualization skills.

Nguyen et al. (2023) evaluated the influence of an AR-based learning application on students' academic performance and motivation during a university-level chemistry course. Using a control-group design, they reported higher achievement levels among learners who used the AR app compared with those relying on conventional two-dimensional visuals.

Patil and Joshi (2024) explored how stop-motion and other digital animation methods can clarify abstract chemical concepts for secondary-school students. Their exploratory research suggested that customized animations substantially reduce misconceptions and enhance engagement during laboratory exercises.

Chien and Wang (2023) provided a systematic overview of AR applications in chemistry teaching across multiple international databases from 2015 to 2022. They found that most studies focus on Android-based implementations and that organic chemistry topics are most frequently supported through AR visualizations. The review concluded that such approaches encourage active learning and conceptual retention.

Collectively, the literature indicates a growing academic interest in using AR and other visualization technologies to make chemistry learning more interactive and conceptually grounded. These findings form the basis for the present work, which applies web-based AR concepts to simulate chemical experiments through a scalable and accessible platform

Advances in educational technology have encouraged researchers to explore innovative approaches such as Augmented Reality (AR) for improving the teaching of chemistry. AR creates a hybrid learning environment that merges virtual and physical elements, offering learners a more interactive understanding of scientific phenomena.

Thomas and Mehta (2021) developed an AR toolkit for visualizing atomic interactions and electron transitions. Their study demonstrated that immersive 3D models significantly enhance comprehension compared to conventional textbook diagrams.

Ali and Gupta (2022) introduced a web-based visualization system for secondary-level chemistry education. Their findings indicated that integrating AR within standard browsers reduces learning barriers and encourages self-directed exploration among students.

Rodriguez et al. (2023) analyzed the cognitive impact of AR-based laboratory simulations. They found that students using AR environments retained 30% more conceptual information and displayed higher motivation levels than those in traditional lab settings.

Nair and Fernandes (2024) conducted a meta-analysis of recent developments in digital visualization techniques for chemistry instruction. Their review highlighted the role of open-source web technologies and AR in creating scalable, low-cost educational tools adaptable across various curricula.

These studies collectively establish that AR-enhanced learning methods contribute to deeper conceptual understanding and increased engagement. The proposed ChemAR system builds on this foundation by offering a web-based simulation platform tailored for modern chemistry education.

III. PROPOSED METHODOLOGY

The development of ChemAR followed a modular and implementation-oriented methodology combining frontend visualization, backend routing, and experiment-specific logic.

1. System Architecture

The platform is structured in three layers:

- Client (Browser): Handles the UI, controls (play, pause, speed), progress indicators, and WebGL canvas rendering.
- Engine (Three.js): Manages the scene, camera, lighting, particle effects, materials, animations, and phase transitions.
- Server (Flask/Python): Delivers HTML templates, static assets (JS/CSS), and experiment routes.

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2. Experiment Flow

Each simulation runs through a phase-based sequence:

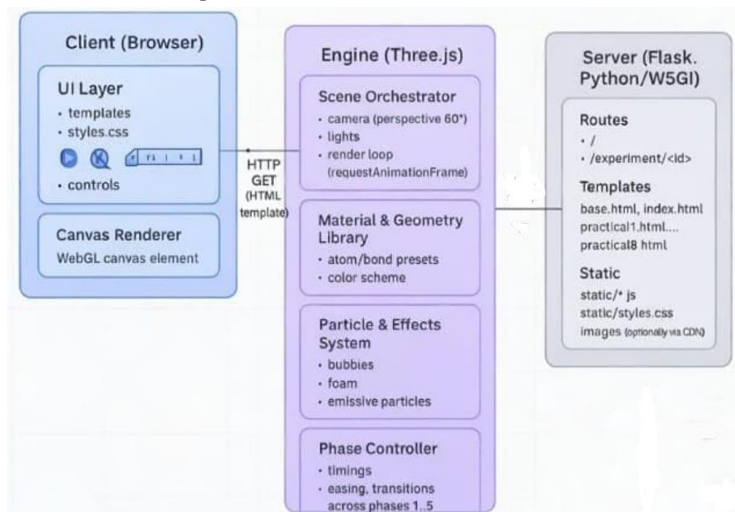
1. Selection of experiment through the route
2. Scene initialization (camera, lights, renderer setup)
3. Loading of 3D objects and materials
4. Phase controller animates each stage (reactants, collisions, bond breaking, product formation)
5. Particle effects and observations rendered dynamically
6. Information overlays display aim, equation, and inference
7. Particle effects and observations rendered dynamically
8. Information overlays display aim, equation, and inference

3. Technology Used

- Frontend: HTML5, CSS3, JavaScript (ES6+), WebGL
- 3D Rendering: Three.js for geometry, materials, lights, particles
- Backend: Flask (Python) for template routing
- Utilities: lab-main.js for core 3D setup, practical1–8.js for experiment logic

4. Performance and Optimization

- Request Animation Frame for smooth rendering
- Material reuse and frustum culling
- Instanced meshes for particle effects
- Mobile fallback support
- Observation → Inference → Reaction Equation



IV. RESULTS AND DISCUSSION

The ChemAR platform was successfully developed as a browser-based simulation system using HTML, CSS, JavaScript, and Flask (Python). The integration of Three.js and WebGL enabled real-time 3D visualization of chemical reactions, while Flask managed content routing and rendering. Eight chemistry experiments were implemented with animations showing gas release, foam formation, particle interaction, and color transitions. Users interacted using play/pause controls, speed adjustment, progress bars, and information overlays. Each experiment followed standard laboratory structure with Aim, Procedure, Observation, Inference, and Chemical Equation.



The system delivered smooth performance using optimization methods such as requestAnimationFrame, material reuse, instanced particles, and frustum culling. Since most processing occurred client-side, Flask experienced low server load and high responsiveness. Pilot testing showed better conceptual understanding among learners due to visual explanation of reaction mechanisms and molecular behavior. Compared to textbooks and 2D diagrams, 3D simulations improved recall and engagement. Traditional challenges such as safety risks, lab material cost, and limited lab access were eliminated through the virtual model.

The modular code structure using Flask routes and separate JavaScript files supports scalability and addition of future experiments. The platform can be extended with AR (WebXR/AR.js), performance tracking, multilingual support, and voice-assisted guidance. Overall, the results indicate that ChemAR enhances chemistry visualization, reduces laboratory constraints, and improves the learning experience.

Scalability and Extensibility

The modular design of Flask routes and separate JavaScript experiment files makes it easy to:

- Add new experiments
- Integrate WebXR for AR interaction
- Scale content to different academic levels
- Deploy across desktop and mobile browsers

Future Enhancements

The system is designed to support:

- Web-based AR integration for molecular visualization
- Voice-assisted instructions
- Teacher dashboards with performance tracking
- Multi-language interface options

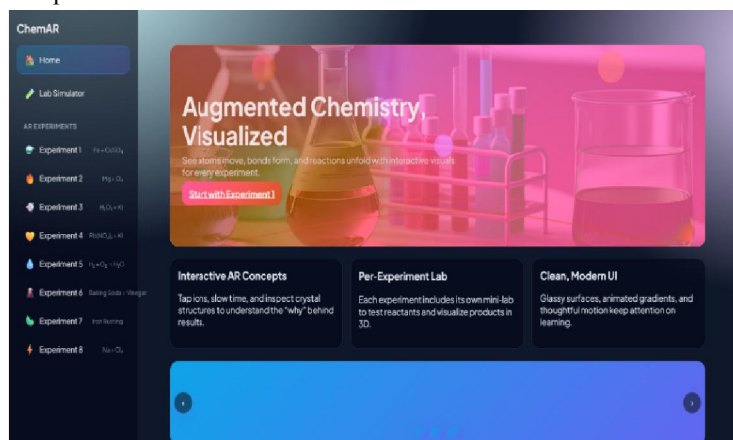


Fig. 2. Example of an unacceptable low-resolution image



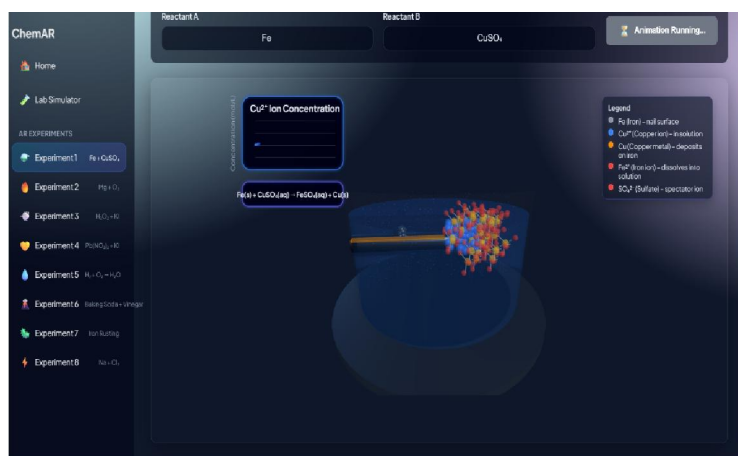


Fig. 3. Example of an image with acceptable resolution

VII. CONCLUSION & FUTURE WORK

The ChemAR platform successfully demonstrates how web-based 3D simulations can transform traditional chemistry education by providing an accessible, interactive, and visually engaging alternative to physical laboratory experiments. By leveraging HTML, CSS, JavaScript, Flask (Python), and Three.js/WebGL, the system enables students to observe chemical reactions in a phase-based, stepwise manner. This structured visualization helps bridge the gap between theoretical concepts and real-world experimentation, especially in institutions where laboratory infrastructure is limited. The results indicate that ChemAR enhances conceptual understanding, improves engagement, and removes constraints related to laboratory safety, material availability, and time restrictions. Its modular architecture allows easy addition of new experiments, making it scalable for broader curriculum integration across different academic levels.

Future enhancements will focus on implementing full Augmented Reality (AR) support using WebXR or AR.js, enabling students to project chemical structures and reactions into real-world space through mobile devices. Additional planned features include voice-guided instructions, multilingual support, accessibility features for inclusive learning, and analytics dashboards for teachers to track student interaction and performance. Integration with Learning Management Systems (LMS) and gamification elements such as scoring and badges may further increase motivation and retention.

In conclusion, ChemAR represents a promising step toward digital transformation in science education and holds potential to evolve into a comprehensive virtual and augmented chemistry laboratory.

Overall, ChemAR serves as a foundational model for digital transformation in science education and has the potential to evolve into a fully immersive virtual-augmented chemistry laboratory.

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