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AR-Enhanced Inquiry Learning in Elementary Science: Developing Students' 4C Skills

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Abstract. This research aimed to develop and evaluate a bounded inquiry laboratory that integrates augmented reality (AR) to enhance students' 4C skills. The 4D model (define, design, develop, and disseminate) was used as research design. Participants in this study were 63 elementary school teachers and 53 fifth-grade students, selected using purposive sampling techniques. The instruments used were an essay test and observation sheets. The results showed that students' critical and creative thinking skills improved with a moderate N-gain category (0.62–0.69), which was higher than the N-gain (0.34–0.44) of the control class. Effect size analysis showed a moderate to large effect, especially in the aspects of thinking as hypothesis testing (0.656) and flexibility (0.704). This indicates that the AR-Bounded Inquiry Lab model is effective in developing critical thinking and flexible problem-solving skills compared to conventional practical work. Furthermore, collaboration and communication skills also showed strong improvements, particularly in oral communication and time management. Practically, the AR-Bounded Inquiry Lab model offers an innovative approach that can be adopted in primary school science learning, while theoretically, this research reinforces the constructivist and dual-coding learning frameworks.

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Further research is recommended to test the application of this model on a larger scale and to examine its long-term impact.

Keywords: augmented reality; elementary science education; bounded inquiry learning; 4C skills

1. Introduction

Indonesia still faces several complex issues in the field of science. The results of research by the OECD (Organisation for Economic Co-operation and Development) through PISA (Programme for International Student Assessment) for 2018 placed Indonesia 71st out of 79 countries (OECD, 2019). In fact, the latest PISA results from 2022 show that Indonesia's science score decreased from 396 in 2018 to 383 in 2022 (OECD, 2023). The data reflect the poor science literacy of Indonesian students. Similarly, when looking at the 4C skills (critical thinking, communication, creative thinking, and collaboration), Indonesian students still lag compared to those in developed countries (Boediono, 2020). Previous studies have shown that Indonesian students' 4C skills remain suboptimal and unevenly distributed across urban and rural areas (Khoiri et al., 2021).

The research findings by Khoiri et al. (2021) indicate that students in urban areas have higher levels of creativity and communication compared to students in rural areas, while students in rural areas demonstrate better collaboration skills. This is evident from the variations in students' 4C skill achievements across regions, as well as the consistently low performance in specific aspects, such as critical thinking. One contributing factor to this condition is the limited capacity of pre-service teachers to design and implement learning activities that are oriented toward 21st-century skills (Nurhayati et al., 2025). This presents a challenge for all relevant authorities to continue innovating in efforts to improve the quality of science education in Indonesia.

One way to address this issue is by innovating science practical activities (Malik & Ubaidillah, 2021) at the elementary school level. Two types of practical activity can be used: real and virtual labs. Since both types of practical activity have their strengths and weaknesses, it is not advisable to compare the two but rather to find ways to combine them (Serrano-Perez et al., 2023; Taghavi & Cohen, 2009; Zacharia & Olympiou, 2011). One way to combine both is through the use of augmented reality (AR) technology.

Several studies have indicated that the integration of technologies such as AR into science education has significant potential to enhance students' conceptual understanding and engagement (Peikos & Sofianidis, 2024; Siki & Leba, 2025), motivation, learning outcomes (Liao et al., 2025), problem-solving skills (Lin et al., 2023), and critical thinking skills (Wen et al., 2023). Augmented reality technology is still rarely used in practical activities (Ismail, Setiawan, et al., 2019). So far, in some countries, such as Turkey, Cyprus, and Mexico, this technology has only been used as a learning medium (Fidan & Tuncel, 2019; Ibáñez et al., 2020; Roumba & Nicolaidou, 2022). A similar situation occurs in Indonesia, where AR has not yet been directly integrated into practical activities (Du et al., 2024; Ismail, Festiana, et al., 2019; Ismail, Gumilar, et al., 2019).

To address the above issues, the use of AR technology alone is not enough; there is a need to select a practical model that emphasizes science literacy and 4C skills. One practical model that can be used is the inquiry model (Allen et al., 1986; Febri et al., 2020; Ural, 2016; Zikrina et al., 2021) because it can be implemented in both real (Ford et al., 2023) and virtual (Lai et al., 2022; Putri et al., 2021) practical activities. Additionally, the inquiry model has the advantage of improving concept understanding (Gumilar & Ismail, 2023), science literacy (Putri et al., 2021), and 4C skills (Affilia et al., 2023; Marbun et al., 2022).

However, research integrating AR into inquiry-based learning or practical models to enhance 21st-century skills (4C) is scant (Papalazarou et al., 2023). Most existing research tends to focus on the impact of AR on motivation and achievement (Liao et al., 2025), or its effect on students' problem-solving skills (Lin et al., 2023). Only a few studies have attempted to combine AR with the inquiry approach directly, such as the study by Wen et al. (2023), which applied AR in inquiry-based learning in the classroom. This indicates a research gap in developing AR-based science practicum models that are systematically integrated with the inquiry approach in primary schools.

From a theoretical perspective, this study is based on constructivist theory (Piaget, 1964), which emphasizes that knowledge is actively constructed through direct experience. In addition, dual-coding theory (Paivio, 2014) forms the basis for integrating visual and verbal information to strengthen conceptual understanding. These two theories support the use of AR as a medium capable of connecting abstract scientific concepts with concrete visual representations, thereby facilitating the process of knowledge construction in students.

This study was designed to involve elementary school students. Therefore, the AR inquiry lab model was developed with a focus on student independence in inquiry activities. This model is named the AR-Bounded Inquiry Lab. It is expected that this lab model will provide new insights into training 4C skills for elementary school students. The following research questions guided this study:
1. How was the AR-Bounded Inquiry Lab model designed and developed?
2. What is the effect of applying the AR-Bounded Inquiry Lab model on improving students' 4C skills?
3. What are students' perceptions of the AR-Bounded Inquiry Lab model?

2. Literature Review

Laboratory activities play a crucial role in science education, as they allow students to directly experience scientific concepts through experiments and observations. By involving students in laboratory activities, they can develop critical thinking skills (Sutiani et al., 2021), problem-solving abilities (Huang, 2022), and an understanding of natural phenomena that may be difficult to explain with theory alone. In addition to thinking skills (mind-on), students can also develop hands-on skills (Wilcox & Lewandowski, 2016) through practical activities. However, one of the main obstacles in conducting laboratory activities is the lack of facilities and infrastructure (Malik et al., 2020). With the use of appropriate tools, learning media, and technology, laboratory activities can help students relate science concepts to real-life situations, making learning more engaging and effective in enhancing their understanding.

One technology that can be used in laboratory activities is AR. The integration of AR into laboratory activities not only enriches the learning experience but also enhances motivation (Khan et al., 2019) and learning effectiveness in the classroom (Ibáñez et al., 2014). The integration of AR into science laboratory activities brings a new dimension that enriches students' experiences in learning science (Ismail, Bhakti, Sari, Dwi Kemalia, & Saprudin, 2024; Ismail, Bhakti, Sari, Dwi Kemalia, & Susilawati, 2024). With AR technology, students can see and interact with abstract phenomena or objects that are difficult to observe directly (Ismail, Gumilar, et al., 2019).

For example, through AR, the movement of electrons in electrical concepts can be presented in a clearer and more engaging visual form. This form of interactive visualization fosters curiosity sustained attention, and self-directed exploration, elements that are central to constructivist learning theory. Constructivism, as articulated by Piaget (1964), emphasizes that learners actively build knowledge through meaningful experiences, particularly when they can manipulate and engage with real or simulated objects in context-rich environments. In this sense, AR-supported laboratory activities provide an ideal platform for promoting active knowledge construction, enabling students to explore, hypothesize, test, and reflect in ways that mirror authentic scientific inquiry.

AR-integrated inquiry-based laboratory activities are in line with 21st-century learning objectives, particularly in the development of 4C skills (Binkley et al., 2012; Trilling & Fadel, 2009). Through AR and practical activities, students can visualize abstract and complex physical phenomena (critical thinking), design creative experimental procedures (creativity), communicate their findings through multimodal representations (communication), and collaborate in a shared digital space (collaboration).

In parallel, dual-coding theory, developed by Paivio (2014), provides an important cognitive perspective on how AR can enhance learning. The theory posits that information is better retained and understood when presented through both verbal and non-verbal (e.g., visual) channels. Augmented reality environments naturally support this dual-channel process by combining textual instructions (e.g., in student worksheets) with real-time visual representations (e.g., 3D animations of molecular structures or physical phenomena). For example, when students read about electric current in a worksheet while simultaneously observing a 3D simulation of electron flow, they engage both verbal and visual processing pathways. This dual encoding promotes the formation of integrated mental representations, thereby improving comprehension and long-term retention.

Importantly, empirical research has shown that integrating AR into science instruction does not necessarily increase cognitive load, and in many cases, it reduces extraneous cognitive demands. Augmented reality-enhanced science reading tasks have been found to improve learning outcomes and motivation while lowering cognitive load (Lai et al., 2019). Furthermore, research has shown that students in AR-based experimental groups achieve the highest knowledge gains and experience the lowest cognitive load compared to 3D and traditional groups (Liu et al., 2021).

However, Elford et al. (2022) noted that, in their research, although AR did not significantly outperform conventional methods in terms of test scores, the perceived cognitive load between the AR and control groups remained comparable. These findings suggest that the effectiveness of AR in reducing cognitive load and enhancing learning is highly dependent on instructional design, especially in relation to content complexity and students' prior knowledge.

Several empirical studies have shown that the integration of AR into science learning can increase motivation, conceptual understanding, and 4C skills in various contexts. Table 1 summarizes the main findings from previous studies that form the basis for the development of the model in this study.

Table 1: Previous studies

Author(s)	Year	Method	Key findings
Ibáñez et al.	2014	Experimental study	AR-supported lab activities improved learning effectiveness and engagement compared to traditional methods
Khan et al.	2019	Quasi-experimental	Integration of AR increased students' learning motivation and participation
Liu et al.	2021	Experimental	The AR group achieved the highest learning gains and the lowest cognitive load
Wen et al.	2023	Mixed methods	AR integrated with inquiry learning improved critical thinking and knowledge creation
Ismail, Bhakti, Sari, Dwi Kemalia, and Saprudin	2024	Design-based research	The AR-based problem-solving lab improved conceptual understanding

As shown in Table 1, most of the studies indicate that AR-based learning environments encourage student engagement, conceptual understanding, and learning motivation, while also developing 21st-century skills such as critical thinking, creativity, and collaboration. These findings provide a strong empirical basis for the development of the AR-Bounded Inquiry Lab model in this study. In summary, the integration of constructivist principles and dual-coding mechanisms within AR-based laboratory learning environments creates an optimal setting for effective science education. When appropriately designed, such environments support active, engaging, and cognitively efficient learning that aligns with both psychological and pedagogical theories.

3. Methodology

3.1 Research Design

The research method employed in this study is research and development (R&D) (Richey & Klein, 2014). The selection of this research model is in line with the main output of this study, which is the development of AR technology products in the problem-solving laboratory model called the AR-Bounded Inquiry Lab. The research design used was the 4D model (define, design, develop, and disseminate), developed by Thiagarajan (1974). The first stage of this research was the definition stage, which involved a needs analysis. The analysis was conducted through interviews with teachers to understand the laboratory activities typically conducted in the field and by reviewing literature on laboratory models and innovative technologies that can enhance problem-solving skills and improve students' conceptual understanding.

Additionally, content analysis was performed to determine which materials were suitable for the developed laboratory model. The next stage was the design stage, where an innovative laboratory framework was created based on the needs analysis of the field, and a storyboard was developed for the AR application that was integrated into the developed laboratory activities. The development stage aimed to develop the application product and student worksheets, followed by expert validation of the developed product.

Finally, the dissemination stage consisted of two main activities: first, testing the compatibility of the developed AR lab application across various Android devices and versions; and second, implementing a limited classroom trial to evaluate the effectiveness of the AR-Bounded Inquiry Lab model. The classroom trial employed a pretest–posttest control group quasi-experimental design involving two classes: a control group (25 students) that used the verification practicum model and an experimental group (28 students) that used the AR-Bounded Inquiry Lab model.

3.2 Participants

The participants in this study consisted of two groups. The first group, in the definition stage, comprised 63 elementary school teachers aged 31–48. The second group, in the dissemination stage, consisted of 53 fifth-grade students aged 11–12, who were divided into two groups: 28 students in the experimental group and 25 students in the control group. The participants in this research were selected using purposive sampling. This technique was chosen because the research specifically required schools and participants who were accustomed to using mobile devices in learning and had previously conducted science laboratory activities. Although the sample size was relatively small, this was justified because the focus of the research was to develop and test a prototype AR application product in practical activities, not to generalise statistical findings.

3.3 Instruments and Data Analysis

The instrument used in the define stage was a questionnaire with elementary school teachers to obtain data regarding the science laboratory activities traditionally conducted in schools. The data obtained were then analyzed using thematic analysis (Gumilar & Ismail, 2023). In the development stage, expert validation rubrics were used to evaluate the AR applications developed for practical activities. The experts' comments were summarized, and revisions were made to improve the developed applications. The instrument used for dissemination was the User Experience Questionnaire (UEQ) (Hinderks et al., 2019). This questionnaire consists of 26 statements outlined by six indicators, as shown in Table 2.

Table 2: Indicators of the User Experience Questionnaire

No.	Indicator	Number of items	Item numbers
1	Attractiveness	6	1, 12, 14, 16, 24, 25
2	Clarity	4	2, 4, 13, 21
3	Efficiency	4	9, 20, 22, 23
4	Dependability	4	8, 11, 17, 19
5	Stimulation	4	5, 6, 7, 18
6	Novelty	4	3, 10, 15, 26
Total items		26	

The UEQ was chosen because its construction is simple, allowing users to quickly complete the questionnaire while still obtaining comprehensive information or data. Additionally, the questionnaire enables users to easily and directly express their attitudes, impressions, and feelings when using the developed AR technology product (Davidavičienė et al., 2020). The UEQ consists of 26 questions with 7 scales of options, ranging from -3 (very bad) to 3 (very good).

The average assessment for each scale range in the questionnaire is then categorized into three value categories: if >0.8, the evaluation of the developed application is considered positive; if the value is between -0.8 and 0.8, the evaluation is categorized as neutral; and if <-0.8, the evaluation is categorized as negative. The reliability value of the UEQ instrument was tested using Cronbach's alpha coefficient with the following values: attractiveness (0.92), clarity (0.83), efficiency (0.80), dependability (0.71), stimulation (0.79), and novelty (0.74).

The second instrument used in this study was the 4C instrument, which includes skills in creative and critical thinking, measured using five essay questions. The aspects assessed for critical thinking skills are *reasoning* and *thinking as hypothesis testing* (Tiruneh et al., 2017), while the aspects measured for creative thinking skills are *fluency*, *flexibility*, and *elaboration* (Handayani et al., 2021; Torrance, 1968). The instruments developed were then analyzed for validity and reliability using SPSS software (Pallant, 2020). The instruments were tested on 20 students at an elementary school in Garut Regency.

The validity analysis of the critical thinking test questions showed that the reasoning questions had a validity value of 0.714, and the thinking as hypothesis testing questions obtained a value of 0.776. Meanwhile, the validity analysis of the creative thinking skills test questions showed that the fluency questions had a validity value of 0.762, the flexibility questions had a validity value of 0.941, and the elaboration questions obtained a value of 0.648. These values indicate that the questions were valid because they exceeded the *r*-table value of 0.468. Meanwhile, the critical thinking test showed a reliability coefficient of 0.650, which is in the sufficient category, while the creative thinking skills test showed a reliability coefficient of 0.705, which is in the high category. Thus, the instrument was declared suitable for use as a research tool.

Furthermore, communication and collaboration skills were measured using observation sheets and analyzed using a Likert scale. The aspects measured in communication skills were: 1) the ability to communicate, in written or oral form, and understand or make others understand various messages in different situations; 2) the ability to listen and understand various oral messages in different communicative situations and speak briefly and clearly; and 3) the ability to write various types of texts for various purposes (Binkley et al., 2012). The aspects of collaboration skills measured were: 1) contribution, 2) time management, 3) task focus, 4) working with others, and 5) responsibility.

To measure how effective the AR-Bounded Inquiry Lab model is, the first step was to convert the critical and creative thinking skills into a scale of 100. The data obtained were then analyzed using N-gain testing (Hake, 1998) to determine how much the students' critical and creative thinking skills improved, with categories shown in Table 3.

Table 3: N-gain categories

N-gain	Category
$G \leq 0.3$	Low
$0.3 < G \leq 0.7$	Medium
$G > 0.7$	High

In addition, effect size analysis (Gignac & Szodorai, 2016; Ismail et al., 2025) was used in this study to measure the magnitude of the impact of the bounded inquiry laboratory model integrated with AR on improving students' critical and creative thinking skills. The criteria for interpreting effect size values (Fritz et al., 2012) are presented in Table 4.

Table 4: Effect size categories

Effect size	Category
0.8	Large
0.5	Medium
0.2	Small

To ensure the accuracy of the statistical analysis results, a series of preliminary and comparative tests was conducted. The Kolmogorov–Smirnov normality test was used to check whether the data were normally distributed. If the normality assumption was met, the analysis of the differences between the experimental and control classes was performed using the independent-samples *t*-test. The non-parametric Mann–Whitney U test was employed as a backup method to compare the two groups if the data were not normally distributed.

4. Results and Findings

4.1 Definition of Needs Analysis

The first stage of this research was the needs analysis stage. This stage involved a needs analysis of the target group (Spatioti et al., 2022), aimed at identifying whether there is a gap between the current situation in the field and the ideal conditions expected. This analysis was conducted through field studies. The field study conducted in this research involved distributing questionnaires to 63 teachers from the Garut district, the Sumedang district, and Tasikmalaya City. Table 5 presents the results of the questionnaire regarding the implementation of practical science activities carried out in schools.

Table 5: Key findings on the implementation and challenges of science practicums in elementary schools

Measured aspect	Main finding	Additional notes
Practicum frequency	46% of teachers conduct practicums 1−2 times per semester, and 35% conduct practicums 3–4 times	Only 9.5% never conduct practicums
Practicum model	The most commonly used models are the problem-solving (46.8%) and inquiry (41.9%) models	Only 12.9% used the verification model and 11.3% used the HOTs-based practicum model
Technology used	Learning videos are the most dominant tool (74.2%)	Only 11.3% of teachers used AR technology
Main obstacles	The biggest challenges are damaged/incomplete equipment (61.3%) and inadequate laboratory space (61.3%)	Student motivation issues are relatively minor (8.1%)
School support	Student motivation is high (61.7%), and 45% of teachers can develop learning models	Only 15% of schools have adequate science laboratories

4.2 Design and Development of the AR-Bounded Inquiry Lab

The next step was the design of the AR-Bounded Inquiry Lab framework model. This practicum model design consisted of three sessions. The first session is the pre-laboratory session, which is conducted at home; the second is the laboratory activity session, which takes place in the laboratory; and the last is the post-laboratory session, which is conducted in the classroom or laboratory. For the pre-laboratory session, there is one stage: start and explain. For the laboratory activity session, there are four stages: discover and produce, evaluate and reflect, organize and manage, and analyze and synthesize. Meanwhile, the post-laboratory session has one stage: communicate and apply. The integration of the AR takes place in the discover and produce stage. The initial framework of the AR-Bounded Inquiry Lab model was developed, as shown in Table 6.

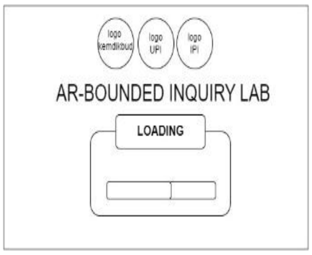
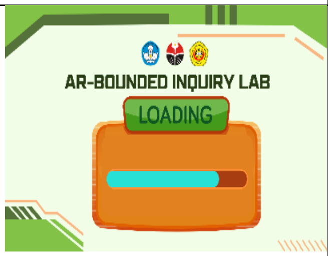
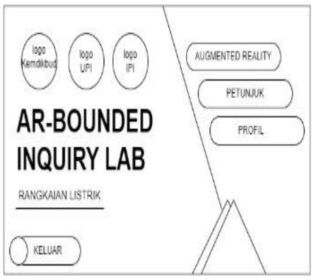
Table 6: Framework model of the AR-Bounded Inquiry Lab

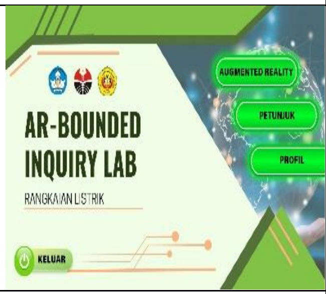
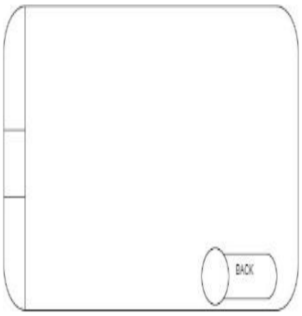
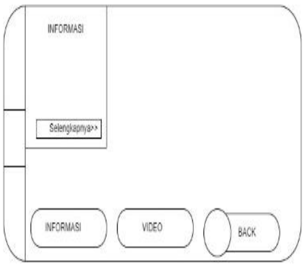
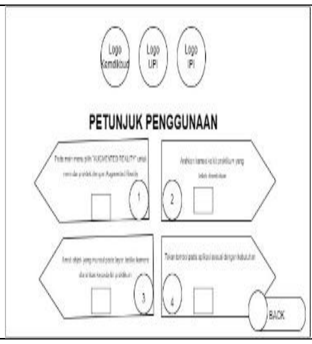
Session	Stage	Skills taught
Pre-laboratory activities	1. Start and explain	• Communication • Critical thinking • Science competency • Knowledge
During laboratory activities	2. Discover and produce	• Critical thinking • Creativity • Collaboration • Procedural knowledge
	3. Evaluate and reflect	• Critical thinking • Competency • Procedural knowledge
	4. Organize and manage	• Collaboration
	5. Analyze and synthesize	• Critical thinking • Epistemic knowledge
Post-laboratory activities	6. Communicate and apply	• Communication • Critical thinking • Scientific/science identity

4.2.1 Design and development of the AR-Bounded Inquiry Lab application

The AR-Bounded Inquiry Lab model in this study was developed with the integration of AR technology. The purpose of this integration is to combine the real-world environment (electricity kit) with the virtual environment in the form of animations (Azuma, 1997). The AR integration in the practicum model is applied during the discover and produce stage using markerless tracking on the electricity kit equipment. The design process of the integrated AR technology begins with creating a storyboard and user interface for the application, as shown in Table 7.

Table 7: Storyboard and user interface of the application

Feature	Storyboard	User interface	Information
Loading Screen			The AR application's splash/ loading screen appears before entering the main menu.
Main Menu			The main menu displays several menu buttons, including the **AR Menu** to access the **AR Camera**, **Instructions Menu**, **Profile**

<table>
<tr><th>Feature</th><th>Storyboard</th><th>User interface</th><th>Information</th></tr>
<tr><td></td><td></td><td>
</td><td>Menu, and Quit buttons.</td></tr>
<tr><td>AR Camera Menu</td><td>
</td><td></td><td>This menu includes a button to view the 3D animations, which are adjusted to the circuit. There is also a Back button to return to the main menu.</td></tr>
<tr><td>3D Animations</td><td>
</td><td>
</td><td>This screen displays the 3D animation. The screen contains three buttons: 1) a Video button for users who wish to watch a video; 2) a Use the Information button to view information about the 3D animation; and 3) a Back button for users to return to the AR menu.</td></tr>
<tr><td>Instructions Menu</td><td>
</td><td>
</td><td>This menu contains step-by-step instructions on how to use the application. It also has a Back button for users to</td></tr>
</table>

Feature	Storyboard	User interface	Information
			return to the main menu.
Profile Menu			This menu displays information about the developers of the AR-Bounded Inquiry Lab.

After the UI creation, the next step was to develop the AR application, with the steps for development shown in Figure 1. The AR technology used in this study employs object-based tracking or 3D object tracking (Oufqir et al., 2020). In contrast, the virtual objects displayed in the application are 3D animation objects.

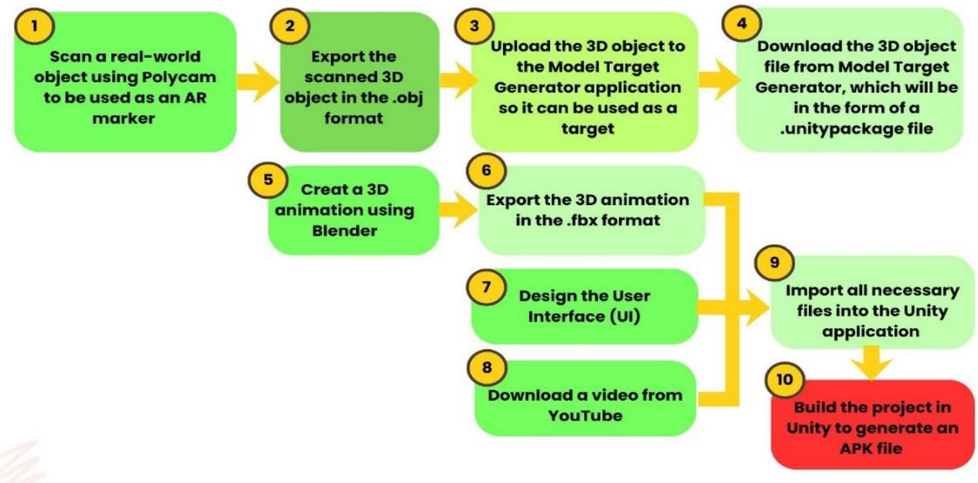
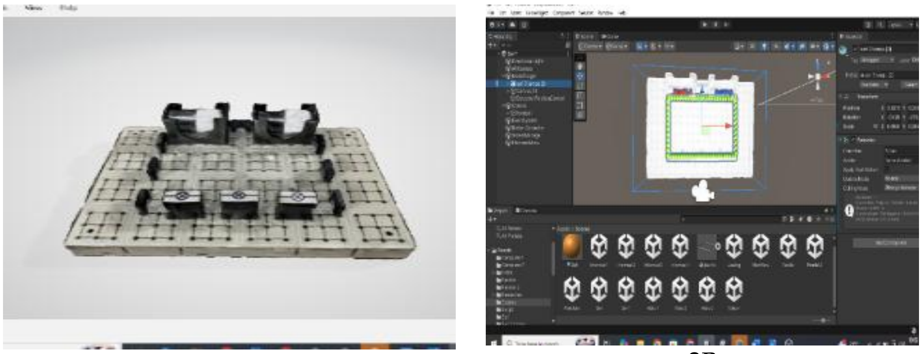


Figure 1: Flow of AR application development

Figure 2 displays the design stages in Polycam and Unity. The first step in developing this AR technology was scanning the real object (Figure 2A) to be used as a marker using Polycam software. The scanned result was then exported into OBJ (Wavefront Object) or FBX (Filmbox) file formats. This marker file can be used as an AR marker in Unity software. The 3D animations were created in Blender. Everything assembled was then imported into Unity software (Figure 2B) to be combined into an application that can be used on Android smartphones.

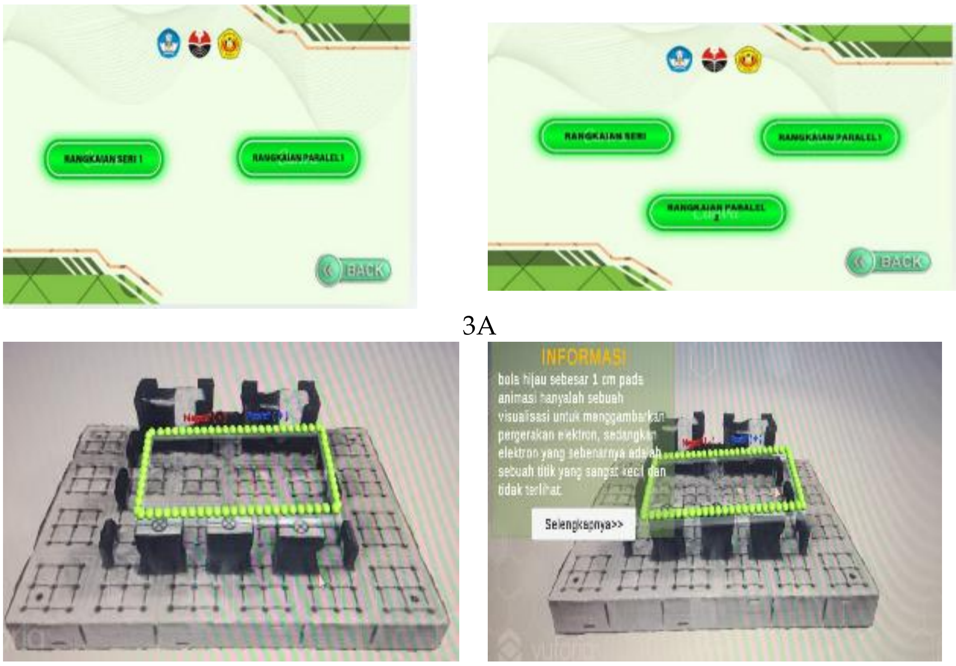


2A 2B

Figure 2: Design stages in Polycam and Unity

Two experts validated the developed application to provide feedback regarding the content of the application so that its quality could be improved (Figure 3). The experts suggested adding one more animation for the parallel circuit showing how the circuit behaves when one light is turned off (Figure 3A). Additionally, to prevent conceptual errors regarding electrons, it was recommended that an **Information** menu be added when students use the AR Camera Menu (Figure 3B).

Before After revision



3A

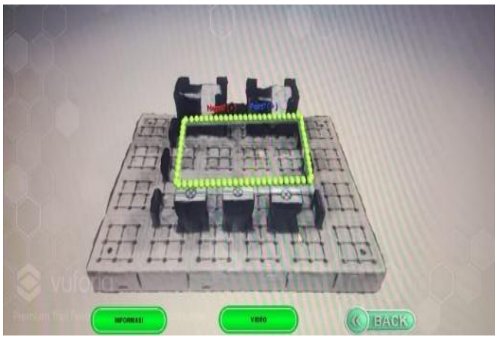
3B

Figure 3: Results of expert revisions

4.2.2 Development of the AR-Bounded Inquiry Lab content

The AR-Bounded Inquiry Lab model was also developed to improve students' understanding at a more comprehensive level. Until now, most students have only understood concepts at the macroscopic level (Anam et al., 2023; Johnstone, 1991). Therefore, innovation is needed so that students can understand concepts not only at the macro level but also at the microscopic level (Kurnaz & Eksi, 2015; Wibowo, 2019). The understanding of microscopic concepts can be enhanced through the visualization of electron movement using AR technology. The modelling of particle movement needs to be visualized with AR technology because many students still believe that electric current is the flow of proton charge from the positive terminal of a battery to the negative terminal (Asy'ari, 2016).

In this research, three animations of electron movement were developed: 1) electron movement in a markerless series circuit (Figure 4A), 2) electron movement in a markerless parallel circuit (Figure 4B), and 3) electron movement in a markerless parallel circuit with the middle light turned off (Figure 4C). The difference in the electron movement animations lies in how the electrons move in the branches of the parallel circuit. In the parallel circuit, the electron flow is divided into different branches, so the number of electrons is less compared to the series circuit.



4A

4B

4C

Figure 4: Electron movement animation

4.3 Dissemination of the AR-Bounded Inquiry Lab

The implementation stage was carried out using two methods: portability testing and usability testing (Supriyono, 2019). Usability testing is the implementation of the AR-Bounded Inquiry Lab application with users, while portability testing is the implementation of the application on various devices.

4.3.1 Portability test

Portability testing is a type of software test that aims to assess how well software or a computer system can be transferred from one environment to another without issues (Supriyono, 2019). The portability test was conducted on the installability aspect. This aspect was tested by installing, running, and uninstalling the application on various devices and OS versions, starting from Android version 11 up to Android version 14. The results of the testing are presented in Table 8, which shows that the AR-Bounded Inquiry Lab application was successfully installed and uninstalled on five different devices. It can therefore be concluded that the application meets the installability standards and can be used on various Android versions with a 100% success rate or validity.

Table 8: Results of testing the application on various devices

No	Device	Android version	Install	Uninstall
1	Vivo Y17S	14	Successful	Successful
2	Vivo Y22	13	Successful	Successful
3	Vivo Y21	12	Successful	Successful
4	Vivo Y16	12	Successful	Successful
5	Redmi 11	11	Successful	Successful

4.3.2 Usability test

Usability testing aims to assess user responses regarding the understandability, learnability, usability, and appeal of the software. The testing was conducted using the UEQ (Hinderks et al., 2019), which contains 26 questions and was distributed to 28 students. The data from the questionnaire results are shown in Table 9.

Table 9: User Experience Questionnaire analysis

Aspect	Score
Attractiveness	2.488
Clarity	2.000
Efficiency	2.259
Accuracy	2.125
Stimulation	2.446
Novelty	2.286

All aspects of the application received scores above 0.8, indicating positive feedback from users. Of the six aspects evaluated, the attractiveness aspect received the highest overall score (2.488). This aligns with previous research showing that AR technology in education can increase students' interest and motivation (Hanafi et al., 2021; Roumba & Nicolaidou, 2022). On the other hand, the clarity aspect received the lowest overall score (2.000). Nonetheless, this lowest score is still well above 0.8, which means the application as a whole received a positive evaluation and is suitable for further use and implementation in practicum activities.

4.4 The Effect of Applying the AR-Bounded Inquiry Lab Model on Improving Students' 4C Skills

The data on the application of the AR-Bounded Inquiry Lab model were analyzed using statistical tests. The results are presented in Table 10. The normality test results showed that the data were not normally distributed, so a non-parametric test using Mann–Whitney U was performed. This test was conducted to obtain information on whether there was a significant difference in student skill scores between the control class and the experimental class. Based on the data obtained, there was a significant difference in the posttest of the control class when compared to the experimental class in critical thinking skills in the aspect of thinking as hypothesis testing and creative thinking skills in the aspect of flexibility. Meanwhile, in the aspects of reasoning (critical thinking) and fluency and elaboration (creative thinking), no significant differences were found between the two classes.

Table 10: Mann–Whitney U test results

Aspects measured		Asymp. Sig.	Decision
Critical thinking skills	Reasoning	0.101	No significant difference
	Thinking as hypothesis testing	0.036	Significant difference
Creative thinking skills	Fluency	0.084	No significant difference
	Flexibility	0.010	Significant difference
	Elaboration	0.130	No significant difference

The implementation was also conducted to examine the effect of the AR-Bounded Inquiry Lab on students' 4C skills. Before and after participating in practical activities using the AR-Bounded Inquiry Lab model, students were given a pretest and posttest to determine the score improvement (N-gain) for critical and creative thinking skills. In addition to the experimental class, there was also a control class. The existence of these two groups allowed for a comparison of learning outcome improvements between classes to determine the effectiveness of the AR-Bounded Inquiry Lab model more accurately. The average pretest and posttest scores, standard deviation (SD), and N-gain scores for students' critical and creative thinking skills are presented in Table 11.

Table 11: N-gain scores for critical and creative thinking skills

Aspect measured	Class	Pretest		Posttest		N-gain	Category
		Avg.	SD	Avg.	SD		
Reasoning	Experiment	48.81	19.21	83.95	16.97	0.69	Medium
	Control	47.22	19.45	75.36	17.72	0.42	Medium
Thinking as hypothesis testing	Experiment	46.43	16.58	81.48	16.80	0.65	Medium
	Control	44.44	16.05	69.56	19.45	0.38	Medium
Fluency	Experiment	44.05	15.85	78.57	20.72	0.62	Medium
	Control	45.33	16.33	69.33	19.05	0.36	Medium
Flexibility	Experiment	46.43	16.58	80.95	21.14	0.64	Medium
	Control	44.00	15.87	68.00	15.15	0.34	Medium
Elaboration	Experiment	47.62	16.80	79.76	16.58	0.61	Medium
	Control	45.33	16.33	73.33	13.61	0.44	Medium

The data in Table 11 show that the students' pretest scores for all aspects were still low, with relatively similar scores below 50 in both the experimental and control classes. After participating in practical activities, the N-gain scores for critical and creative thinking skills in all aspects showed a moderate increase for both the control and experimental classes. Although both were in the same category, the increase in the experimental class showed higher values, ranging from 0.69 to 0.62, while the increase in the control class was relatively lower, ranging from 0.44 to 0.34.

To determine the effect of the AR-integrated Bounded Inquiry Lab model on students' critical and creative thinking skills, effect size analysis was employed (Table 12).

Table 12: Effect size test results

Aspect measured		Class	Mean	SD	Sample	Effect size
Critical thinking skills	Reasoning	Experiment	83.95	16.97	28	0.495
		Control	75.36	17.72	25	
	Thinking as hypothesis testing	Experiment	81.48	16.80	28	0.656
		Control	69.56	19.45	25	
Creative thinking skills	Fluency	Experiment	78.57	20.72	28	0.464
		Control	69.33	19.05	25	
	Flexibility	Experiment	80.95	21.14	28	0.704
		Control	68.00	15.15	25	
	Elaboration	Experiment	79.76	16.58	28	0.423
		Control	73.33	13.61	25	

The results indicate a medium effect, which indicates that the application of the AR-Bounded Inquiry Lab model has a significant impact on improving students' critical and creative thinking skills compared to the control class practicum. The thinking as hypothesis testing aspect showed the highest effect size value of 0.656, which means that the AR-Bounded Inquiry Lab model is most effective in improving students' critical thinking skills in this aspect. Meanwhile, in terms of creative thinking skills, the flexibility aspect also showed the greatest effect, with an effect size value of 0.704. Meanwhile, the reasoning, fluency, and elaboration aspects had relatively lower effect sizes (0.495, 0.464, and 0.423) but were still in the moderate category, thus still indicating that this model contributed positively to the development of students' critical and creative thinking skills.

Meanwhile, communication and collaboration skills were assessed using observation sheets during the practical activities in which students utilized the AR-Bounded Inquiry Lab model. Each student in the group was evaluated using a Likert scale ranging from 1 to 4. The assessment results of students' collaboration skills after participating in the AR-Bounded Inquiry Lab practical activities, as shown in Table 13, indicate that collaboration skills achieved scores between 75% and 89%. In comparison, communication skills, as shown in Table 14, indicate that students' oral communication skills reached 80.36%, which is higher than their written communication skills, at 79.76%.

Table 13: Results for collaboration skills

No	Aspects measured	Score	
		Avg.	%
1	Contribution	3.11	77.70
2	Time management	3.57	89.30
3	Focus on tasks	3.29	82.10
4	Collaboration	3.14	78.60
5	Responsibility	3.04	75.90
Average		**3.20**	**80.70**

Table 14: Results for communication skills

No	Aspect measured	Score	
		Avg.	%
Presentation process (oral communication)			
1	Mastering presentation materials	3.04	75.90
2	Volume of voice	3.43	85.70
3	Presentation explanation articulation	3.18	79.50
4	Material explanation	3.00	75.00
5	Ability to listen and understand presentation explanations	2.86	71.40
Average		**3.21**	**80.36**
PowerPoint (written communication)			
6	PowerPoint text	3.29	82.10
7	PowerPoint design	3.14	78.60
8	Presentation material	3.14	78.60
Average		**3.19**	**79.76**

5. Discussion

The study revealed that the AR-Bounded Inquiry Lab model significantly improves students' 4C skills, particularly their ability to think critically and creatively. When all aspects are considered, the N-gain scores were in the moderate range (0.61–0.69). Compared to the N-gain scores (0.34−0.44) of the control class, the increase in N-gain scores in the experimental class showed higher results in all aspects of critical and creative thinking skills. This indicates that the application of the AR-Bounded Inquiry Lab model has a stronger learning impact than conventional practicums. In particular, the aspects of thinking as hypothesis testing and flexibility showed the most significant differences. The strong improvement in these two aspects may be due to the inquiry structure in the AR-Bounded Inquiry Lab model, which requires students to design their own experiments, make predictions, and adjust procedures based on direct visual feedback from AR. Meanwhile, other aspects such as reasoning, fluency, and elaboration showed moderate improvements, which are likely due to time constraints and students' lack of prior experience in using AR technology, resulting in suboptimal scientific exploration and communication.

The effect size analysis results also support these findings, with values falling into the large category, where the highest value of 0.704 was found in the flexibility aspect and 0.656 in the thinking as hypothesis testing aspect. These findings indicate that AR-assisted inquiry activities encourage students to be more active in constructing, testing, and evaluating hypotheses—an important step in the scientific inquiry process. The relatively lower effect size values in other aspects indicate that although AR can improve visualization and engagement, consistent practice and longer learning time are needed to achieve in-depth mastery in the aspects of reasoning and elaboration.

These findings corroborate past studies that demonstrate how inquiry-based learning can improve students' ability to think more critically (Irwanto et al., 2019; Verawati et al., 2022). The findings also align with previous research showing that AR can provide immersive, real-world learning experiences that encourage higher levels of cognitive engagement (Gudyanga, 2024; Poveda-Mora et al., 2024). The results of studies on teamwork and communication are encouraging. The average score for students' collaborative skills was 80.7%; however, their oral communication skills (80.36%) were slightly better than their written communication skills (79.76%). These findings show that using the AR-Bounded Inquiry Lab can encourage student participation and communication during experiential learning. In line with the research by Vázquez-Cano et al. (2020) and Boonbrahm et al. (2016), the AR-based learning environment encourages students to explore, discuss, and build understanding collaboratively.

However, there are several obstacles to widespread use at the implementation stage, including the availability of electrical kits as AR markers and student ownership of mobile devices, among other infrastructure limitations. Additionally, only about 11% of instructors are familiar with AR (Ismail, Setiawan, et al., 2019), suggesting that teachers have a relatively low level of technological competence. This implies that teacher training programs are required to optimize the use of AR in the inquiry paradigm.

This difficulty is in line with previous research that discovered a number of obstacles, including device and infrastructural limitations, that still stand in the way of implementing AR in the classroom. The implementation of AR requires large development costs and is highly dependent on the availability of suitable hardware and software, according to Kye et al. (2021). This is corroborated by Takrouri et al. (2022), who claimed that not all students having mobile devices that can use AR is an obstacle to its widespread implementation. Furthermore, Parsons and MacCallum (2021) emphasized that teachers are still not proficient in using AR technology and that AR use cannot yet fully replace real-world practice. Therefore, even though AR has demonstrated the potential to improve the quality of education, its successful implementation in schools still hinges on the availability of devices, teacher capacity training, and infrastructure support.

Overall, the AR-Bounded Inquiry Lab model has proven effective in improving students' critical thinking, creativity, communication, and collaboration skills. Despite challenges related to infrastructure and teacher readiness, the integration of AR into inquiry-based practical work is a potential step towards transforming science learning while addressing 21st-century skill requirements.

6. Conclusions

1) The AR-Bounded Inquiry Lab framework model designed in this study includes six stages: 1) start and explain, 2) discover and produce, 3) evaluate and reflect, 4) organize and manage, 5) analyze and synthesize, and 6) communicate and apply. This model specifically integrates AR technology into the discover and produce stage, aiming to enhance students' critical thinking, creativity, collaboration, and communication skills.
2) In addition, based on the results obtained, the AR-Bounded Inquiry Lab application effectively enhances students' 4C skills (critical thinking, creative thinking, collaboration, and communication). The practical implementation significantly improves critical and creative thinking, with moderate N-gain scores. Collaboration and communication skills also showed strong improvements, particularly in oral communication and time management.
3) The results of the usability testing indicate that the application demonstrates strong user appeal and a generally positive user experience. Among the six evaluated dimensions, attractiveness received the highest mean score (2.488), whereas clarity recorded the lowest (2.000). Nevertheless, even the lowest score substantially exceeded the minimum benchmark of 0.8, suggesting that the application, overall, was positively evaluated by users. However, the lowest score in the clarity aspect indicates that the appearance and navigation of the application still need to be simplified to make it easier to use for teachers and students, especially those who are not familiar with AR technology. This is important feedback for the development of the next version of the AR-Bounded Inquiry Lab model.

The main advantage of this model lies in the integration of AR into the inquiry practicum model, thereby overcoming the limitations of real laboratories that cannot display visualizations, while fostering students' higher order thinking skills. The model can also be adapted to various science learning contexts, in schools both with and without adequate laboratory facilities. Further research is recommended to test the long-term effectiveness of this model, develop a lighter AR version that can be implemented in schools with limited devices, and expand its application to other science fields and different levels of education. These results suggest that the AR-Bounded Inquiry Lab is a promising educational tool for fostering 21st-century skills in students.

7. Conflict of Interest, Acknowledgments, etc.

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