

# Design of Virtual Physics Experiments for Secondary Education Driven by Mathematical and Physical Simulation Results

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**Abstract:** Addressing the challenges of limited experimental resources under the requirement of inclusive education for all students, as well as the evolving characteristics of learners in the era of digitalization and intelligent technologies, this study proposes a methodology for designing virtual physics experiments in secondary education driven by mathematical and physical simulation outcomes. Focusing on the "Force and Motion" unit from the Grade 8 curriculum published by Jiangsu Science and Technology Press, the research examines the additional resource requirements and the scope of experimental content. Furthermore, it analyzes how this approach effectively cultivates key competencies, integrates advanced educational paradigms, and employs innovative technological tools to enhance teaching and learning.

**Keywords:** Secondary Education; Physics Instruction; Virtual Experiments; Simulation

## 1. Overview

Over the years, the core objectives of junior secondary school physics education have undergone a progressive evolution through distinct phases: initially emphasizing the explanation of conceptual knowledge, subsequently breaking down fundamental knowledge and essential skills, and currently focusing on the attainment of "three-dimensional" goals alongside cultivating key competencies. Presently, the key

competencies in junior secondary school physics encompass physical concepts, scientific inquiry, scientific reasoning, and scientific responsibility and attitudes, as illustrated in Figure 1.

Physics experiments serve as a vital practical component within physics education, playing a crucial role in the establishment of key physical concepts and fundamental laws, as well as supporting interdisciplinary practical activities. Through case studies, He has elucidated how experimental engagement enhances students' comprehension of physical concepts and elevates their key competencies [1].

Building upon multi-level analyses of existing research, this paper examines the dynamic constraints imposed by striving to provide effective experimental teaching resources to all students. It also addresses the distinctive contemporary challenges characterized by fragmented early exposure, multi-sensory learning absorption, densely populated classes, and limited autonomous learning space. In response, a design methodology for junior secondary school virtual physics experiments driven by mathematical and physical simulation results is proposed. Using the "Force and Motion" unit from the Jiangsu Science and Technology Press edition Grade 8 curriculum as a case study, the paper explores inquiry-based subject design and interactive backend support for students. Finally, it analyses the efficacy of this approach in fostering key competencies, integrating progressive educational philosophies, and applying innovative technological methods.

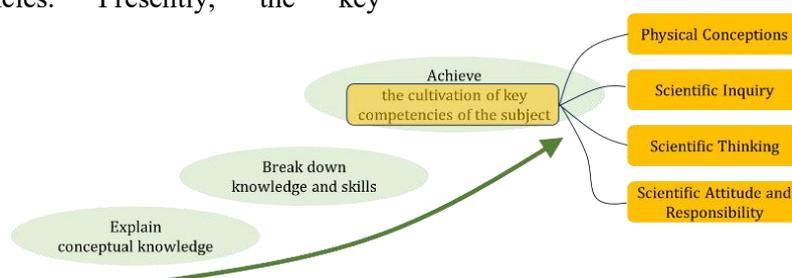


Figure 1. Core Objectives and Disciplinary Competencies of Junior Secondary School Physics

## 2. Design of Physics Experiments in Secondary Education and Contemporary Challenges

### 2.1 Physics Experiment Design and Secondary Physics Instruction

In accordance with authoritative guidelines such as the Opinions on Strengthening and Improving Experimental Teaching in Primary and Secondary Schools and the Compulsory Education Physics Curriculum Standards (2022 Edition), the Basic Catalogue of Junior secondary school Physics Experiments has been promulgated. This catalogue ensures a unified foundation and standardized core requirements while granting junior secondary schools and physics teachers considerable autonomy in experiment design and pedagogical implementation. Existing research in this domain reveals three prominent characteristics:

Firstly, an unwavering emphasis on cultivating key competencies. Zhao underscored the significance of designing and evaluating junior secondary school physics experiments from the perspective of key competencies [2]. Liu & Liu employed a learning sciences framework to investigate experimental design in junior secondary school physics, using the teaching of “series and parallel circuits” as a case study to explore strategies aimed at enhancing students’ comprehensive physics abilities and key competencies [3]. Zhang analyzed the “Investigation of the Imaging Principles of Convex Lenses” experiment from Shanghai and Guangdong versions of junior secondary school physics textbooks, elucidating experimental teaching strategies grounded in core competency development [4]. Zhang further examined details such as problem-scenario creation, fostering autonomous inquiry, reinforcing experiment design and operation, promoting collaborative communication, and emphasizing reflective evaluation. Jin, recognizing the elevation of scientific thinking as a pivotal element of physics key competencies in the Compulsory Education Physics Curriculum Standards (2022 Edition), addressed the balance between junior secondary school physics content volume and competency cultivation. Using “measuring liquid density” as an instructional example, Jin proposed a restructured experimental teaching pathway incorporating a “concentrated pre-training on measurement instruments”

strategy, alongside a “tiered experiment design” model that integrates foundational skill instruction [5].

Secondly, the dynamic integration of progressive educational philosophies. Song et al. introduced the STSE (Science, Technology, Society, Environment) educational concept into the design and delivery of junior secondary school physics experiments [6], leveraging information technology such as noise measurement techniques to create authentic contexts that encourage students to identify and resolve problems. Zeng [7] and Liang [8] emphasized the principle of “life as education”, implementing life-centered physics experiments in teaching. They distilled the core connotations of experiment design, experimental contexts, procedures, and apparatus as being intimately connected with everyday life, employing methods that integrate junior secondary school physics with life-relevant instruction. Under the guidance of learning progression theory, Wang explored the interrelation between fluid pressure and flow velocity through scaffolding learning contexts and constructing cognitive “steps” aimed at synchronously advancing conceptual understanding and scientific reasoning [9]. Wu investigated the application of the 5E instructional model in junior secondary school physics teaching, demonstrating its alignment with curricular philosophies and objectives through the example of the “friction” unit, and proposed practical recommendations for implementing the 5E model [10].

Thirdly, the proactive adoption of new quality productive forces. Gao [11] and Ding [12] combined innovative experimental design with deep learning methodologies, examining how such fusion enhances the depth of students’ comprehension of physics concepts and bolsters their ability to apply knowledge in practice. Notably, AI-driven virtual physics experiments, exemplified by NB Scientific Experiments, have advanced from technological demonstrations to iterative commercial products. Their comprehensive coverage of textbook editions, timely access to key subjects, operability throughout experimental processes, and the capacity to render experimental results vividly have established them as indispensable aids for students’ preview and independent study activities.

### 2.2 Challenges in Designing Junior Secondary

### School Physics Experiments under Contemporary Conditions

The fundamental approach to designing junior secondary school physics experiments must closely adhere to the principles of education, aligning with both the natural laws of teaching and the developmental characteristics of students' physical and mental growth. It should inclusively address the needs of all learners while prioritizing the cultivation of independent thinking, creativity, and practical skills. This framework is depicted in Figure 2.

Around 2020, Zheng & Zhu concentrated on the comprehensive landscape and developmental trends of Education Informatization 2.0, identifying critical obstacles in junior secondary school physics experimental teaching—namely, misconceptions in pedagogical philosophy, a relatively monotonous organizational mode, and superficial application of instructional technologies—and accordingly proposed targeted strategies [13]. Subsequently, Qian's research highlighted that the development and utilization of junior secondary school physics curricular resources from a STEAM perspective could foster novel pathways for integrated education [14]. These studies, conducted at varying analytic levels, emphasize that within the dynamic constraints of “all students” and the availability of effective experimental teaching resources, the implementation of experiment design must holistically consider three pivotal dimensions: pedagogical philosophy, instructional organization, and educational technology.

In the present and foreseeable future, the rapid iteration of advanced technologies within the socio-economic domain profoundly shapes the physical and psychological development environment of adolescents. This results in pronounced regional and group characteristics, as well as inherent individual differences among junior secondary school students in terms of the scale and quality of information exposure and its congruence with the physics curriculum.

(1) Taking artificial intelligence as an exemplar, regions and families with relatively higher economic levels tend to have widespread availability and frequent use of embodied AI devices or internet-enabled AI-supported household appliances, personal terminals, and transportation tools. This phenomenon manifests in two key ways: First, there is a concentrated surge of cutting-edge, specialized disciplinary

terminology, accelerating students' premature exposure and passive reception, albeit with an increased degree of fragmentation. Second, the post-processing of multimedia and intelligent rendering enriches the modes of information presentation, engaging multiple sensory channels—such as auditory, visual, electric, and electromagnetic media—thereby elevating students' thresholds for novelty and pleasure in classroom instruction.

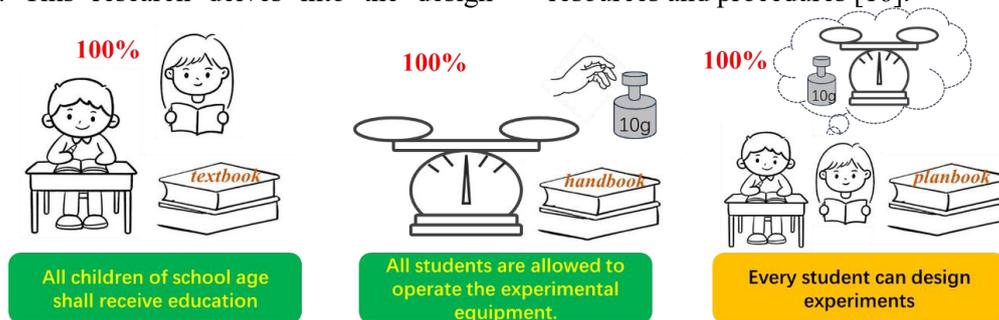
(2) Moreover, in certain areas, population birth peaks coincide critically with the spatial constraints of urban environments and school campus capacities, resulting in frequently overcrowded classes and constrained experimental venues.

Collectively, these influences give rise to a pattern characterized by “fragmented early exposure, multisensory tolerance, crowded classes, and limited autonomy”. The degree and likelihood of such impacts intertwine with the diversification trends of socio-economic factors. Consequently, the design of junior secondary school physics experiments confronts unprecedented challenges: based on the divergent physical and psychological developmental contexts that generate regional group traits and natural individual differences, it must universally target all students to cultivate integrated capacities in thinking, innovation, and practice. Simultaneously, it must reconcile a series of conflicts, including diversified textbooks coupled with standardized experimental assessments, mass-scale teacher training tempered by teacher proficiency disparities, and the competing demands of varied experimental apparatus against constrained funding. These tensions collectively magnify the dynamic constraints between “all students” and the effective resources for experimental teaching.

Since 2025, the nation has embarked upon major initiatives such as the “Construction and Application of Experimental Teaching Resource Systems for Secondary School Physics Curriculum in the New Era” (a major project under the Ministry of Education's strategic planning). This ambitious endeavor aims to systematically address the disjunction between experimental teaching resources and the cultivation of key competencies through comprehensive investigations into the current status of secondary school physics experiments, the establishment of frameworks for physics

experimental resource systems, the integration and development of experimental resources, the application and practice of teaching resources, as well as rigorous evaluation and refinement of their effectiveness. These efforts seek to provide robust theoretical support and practical pathways for deepening physics curriculum reform. Concurrently, Li has explored the deployment of intelligent devices to furnish data support and simulate scenarios, thereby reducing the complexity of experimental operations and stimulating students' intrinsic curiosity for inquiry. This research delves into the design

principles, practical methodologies, and optimization strategies for AI-assisted home experiments in junior secondary school physics [15]. Addressing the limitations of traditional physics experiments whereby apparatuses are directly presented and students are relegated to passive “interpretation”, Jiang advocates for a paradigm shift favoring increased incorporation of “modeling” over “explanation.” This approach aspires to construct and nurture an environment that grants students greater openness and agency regarding experimental resources and procedures [16].



**Figure 2. Developmental Stages of Junior secondary school Physics Experiment Instruction**

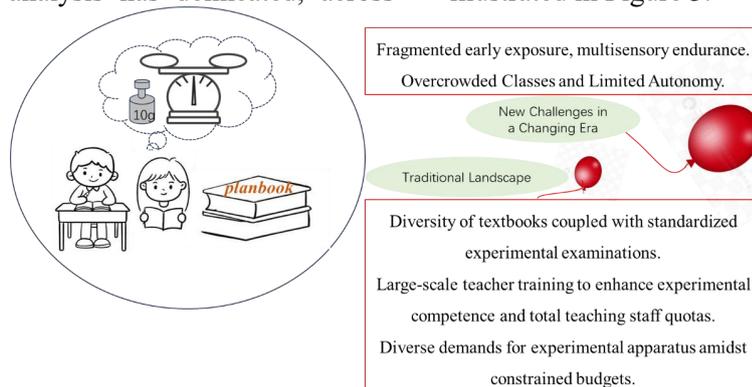
### 3. Design of Virtual Physics Experiments for Junior Secondary School Driven by Mathematical and Physical Simulation Results — Principles, Procedures, and Evaluation Methods

#### 3.1 Concepts and Underlying Principles

##### (1) Background

The preceding analysis has delineated, across

multiple dimensions, the dynamic constraints between “all students” and effective experimental teaching resources, reflecting the entrenched challenges confronting this study. Under emerging circumstances characterized by “fragmented early exposure, heightened multisensory receptivity, widespread overpopulated classes, and limited autonomy”, these tensions have been further exacerbated, as illustrated in Figure 3.



**Figure 3. The Dynamic Constraints between “All Students” and Effective Experimental Teaching Resources**

This paper centers on the comprehensive implementation of secondary education imperatives, which emphasize alignment with educational principles and students' physical and psychological development, inclusivity of all students, and focused cultivation of independent thinking, innovation, and practical abilities.

Within this framework, it proposes a methodology for designing junior secondary school virtual physics experiments driven by mathematical and physical simulation results, encapsulated in the following core tenets:

First, to fully harness the low-cost, high-fidelity advantages of digital modeling and

mathematical-physical simulation, thereby mitigating the dependence of real-world physical experiments on scarce resources and high costs; Second, to resolve the pivotal limitation of constrained experimental teaching resources, thereby enabling interactive, individualized student engagement; Third, by integrating digital asset management and scheduling within teaching communities, to potentially rejuvenate the systemic underpinnings of digital and virtual experimental instruction.

(2) Conceptual Connotation

Mathematical and physical simulation refers to the integration of high-fidelity computer-aided modeling (CAD), large-scale, highly reliable numerical computations, and other foundational technologies to digitally resolve objects, boundaries, and other elements according to mathematical equations that characterize typical physical processes in a temporal sequence, as illustrated in Figure 4. Specifically, high-fidelity computer-aided modeling spatially discretizes physical entities, while large-scale, reliable numerical computations solve the governing mathematical equations of the physical phenomena. In domains such as engineering

design and scientific research, mathematical and physical simulation underpins the practical realization of methodologies like digital twins. When synergized with artificial intelligence, it enables pioneering applications such as one-click generation of three-dimensional videos from textual scripts.

Mathematical and physical simulation-driven design entails utilizing existing multimedia teaching apparatus as the principal operational platform, transforming conventional animated illustrations and dynamic demonstrations into simulation-driven, realistic instructional presentations. Figure 5 depicts the operational schematic of this simulation-driven approach (using the example of spring elongation and deformation): parameters of the experimental procedure, once confirmed via interactive control on classroom teaching displays or computers, are transmitted through the campus network to a backend computing system, which rapidly executes the mathematical and physical simulation of the spring's tensile deformation. The resultant simulation data is then returned over the network to the classroom display or computer, processed for visualization, and exhibited accordingly.

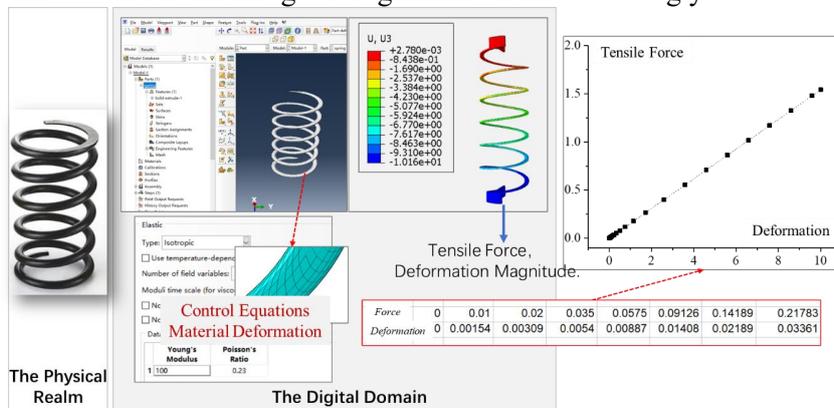


Figure 4. Principle of Mathematical and Physical Simulation Exemplified by the Tensile-Deformation Process of a Spring

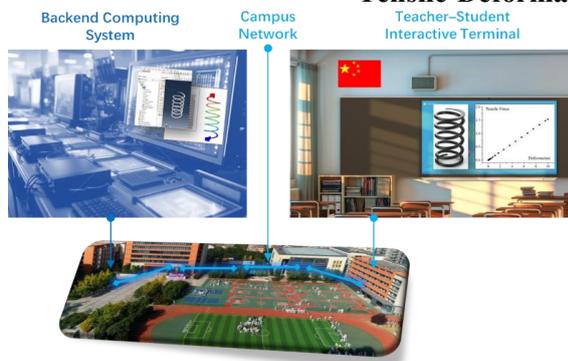


Figure 5. Operational Schematic of Simulation-Driven Execution

3.2 Process

The comprehensive workflow is segmented into key stages: experimental scenario analysis, distribution of procedural elements, mathematical and physical virtual simulation, and simulation result-driven feedback.

During the experimental scenario analysis phase, teachers guide students in deliberating on foundational knowledge and everyday life insights pertinent to the physics experiment subject matter, thereby accelerating the refinement and alignment of the inquiry toward

the experimental theme.

In the procedural elements distribution phase, students propose specific parameter variation ranges for the physics experiment, facilitating a progression from sequential experimental operations to nuanced, problem-focused adjustments within a confined scope.

The mathematical and physical virtual simulation phase leverages underlying technologies such as artificial intelligence to transform front-end information into specialized backend simulation parameters. Concurrently, it employs blade-style high-performance computing servers and dedicated numerical analysis software resources to execute rapid computations and construct dynamic response models that reflect students' queries and parameter adjustments.

Finally, in the simulation result-driven phase, the backend simulation data is integrated with

instructional electronic display systems, enabling data fusion, loading, and visualization for enhanced pedagogical interaction.

### 3.3 Evaluation Method

The multidimensional evaluation is conducted according to the matrix presented in Table 1, encompassing aspects such as the alignment of interactive interface functionalities with knowledge points and the degree of experimental interactivity. The scores from these two domains are weighted proportionally.

During implementation, evaluations are performed through questionnaires, on-site sampling, and other methods. Score assignments for each grade tier and overall standards should be determined through comprehensive studies considering different curricular units and regional school contexts.

**Table 1. Weighted Assessment Technique**

	Alignment with Knowledge Points (Interactive Interface Functions)					Experimental Interactivity					Remarks
	A	B	C	D	E	A	B	C	D	E	
Teacher Segment	A	B	C	D	E	A	B	C	D	E	Weight: 40%
Student Segment	A	B	C	D	E	A	B	C	D	E	Weight: 60%

## 4. Case Study of the “Force and Motion” Unit

### 4.1 Additional Resource Requirements

The additional resources delineated herein refer to those exceeding the standard hardware and software configurations typically found in general secondary school digital infrastructure.

#### (1) Computing Equipment

Device: Portable Computer

Key Specifications:

Processor: Intel(R) Core (TM) i7-10510U CPU @ 1.80GHz, up to 2.30 GHz

Memory: 16.0 GB RAM (15.8 GB available)

Storage: 477 GB SSD (WDC PC SN730 SDBPNTY-512G-1027)

Graphics: NVIDIA GeForce MX250 (2 GB), Intel(R) UHD Graphics (128 MB)

System Type: 64-bit operating system, x64-based processor

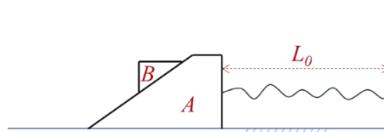
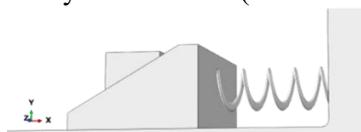
#### (2) Software

Finite Element Analysis Software (for backend

mathematical and physical simulation computations): DS Simulia 2020 version  
Scientific Analysis and User Interaction Platform: MATLAB R2022b version

### 4.2 Experimental Subject Overview

The experiments described in this study primarily focus on the fundamental phenomenon of spring elongation and deformation, while also incorporating verification of the theoretical concept of “elastic force” between objects. The specific experimental setup is illustrated in Figure 6: a spring of length  $L_0$  is horizontally affixed to a wall on one end, with the other end rigidly connected to block A. Block B is placed on the inclined surface of block A. When the combined assembly A-B is pulled horizontally to the left, the spring gradually extends to length  $L$ . Due to the frictional force exerted by the ground on block B, within a certain range of  $L$ , the A-B assembly remains stationary.



**Figure 6. Experimental Setup Configuration**

The inquiry-based experimental tasks encompassed in this study are as follows:

1) Question: When the spring is at its natural length, how does the force exerted on block B

change as the incline angle of block A’s surface is gradually increased?

2) Question: If the A-B assembly remains stationary while the spring is stretched from its natural length  $L_0$  to  $L_1$ , given the spring constant  $k$  and the total mass of the A-B assembly  $m_{AB}$ , what is the coefficient of static friction between block A and the ground?

3) Question: If the coefficient of static friction between block A and the ground increases, while the spring constant  $k$  and the total mass  $m_{AB}$  remain unchanged, how will the extension

length  $L_1$  be affected?

4) Question: Generally, whether on a concrete or tiled surface, some degree of deformation capacity exists. Using imagination, depict the action and reaction forces between block A and the ground, as well as the localized elastic deformation.

The student-interactive interface is illustrated in Figure 7 and Figure 8, while the backend parameters allowing students to modify or specify experimental object attributes are shown in Figure 9.



Figure 7. User Interaction Interface Design

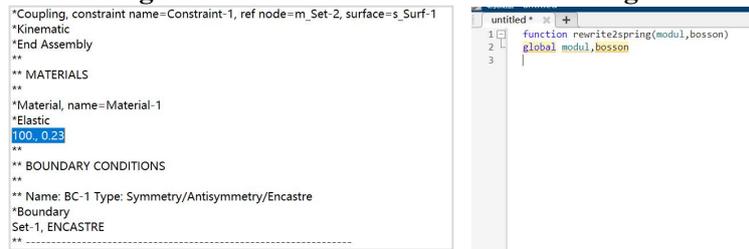


Figure 8. Implementation and Parameterization of the Spring’s “Softness and Stiffness” Adjustment Feature

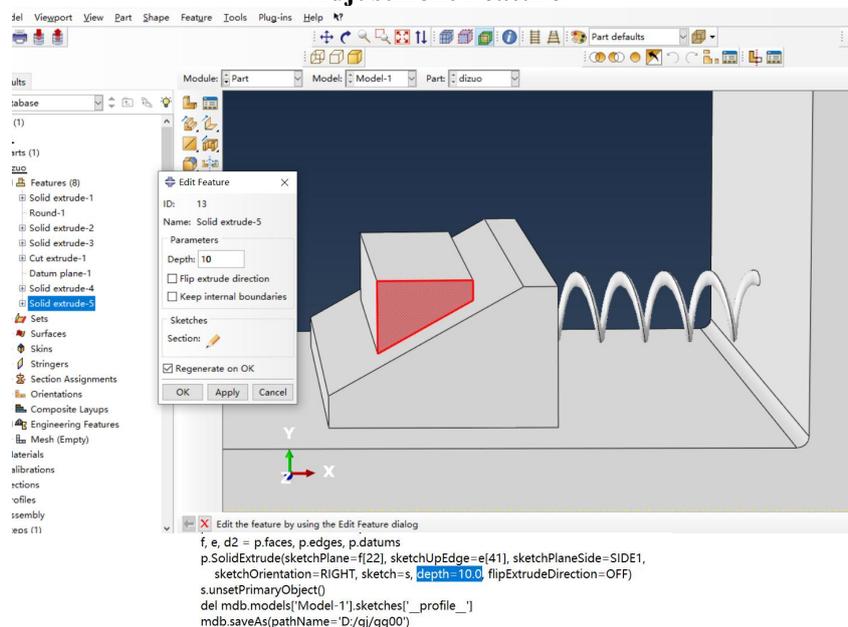


Figure 9. Backend Parameter Status Supporting Student Modifications or Specifications (Example: Block Width)

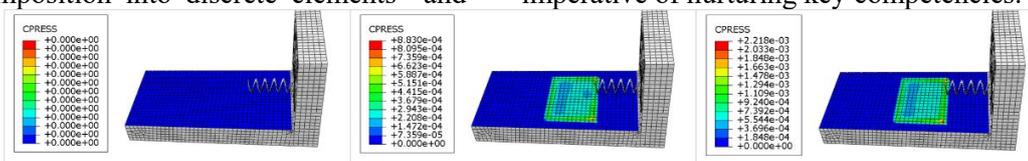
4.3 Analysis of Advancement and Innovation

In a comprehensive view, the methodology outlined in this study harnesses innovative technologies such as mathematical and physical

simulations, supports lightweight deployment, and facilitates interactive engagement, while embracing advanced educational philosophies. For example, the three-dimensional visualization of elastic deformation and forces (Figure 10)

utilizes an intuitive background grid to incorporate scientific reasoning approaches such as “decomposition into discrete elements” and

“limit approximation”. This approach thoroughly embodies the fundamental imperative of nurturing key competencies.



**Figure 10. Visualization of Elastic Deformation of the Ground under the Influence of the Block (With Manually Controlled Proportions of Load Application at 0%, 40%, and 100%)**

## 5. Conclusion

This study integrates the dynamic constraints of student scale and experimental teaching resources with the distinctive characteristics of contemporary student cohorts into a unified perspective, thereby proposing a design methodology for virtual physics experiments in junior secondary education driven by mathematical and physical simulation outcomes. Centered on the foundational concept of spring extension and deformation, and exemplified through the “Force and Motion” unit from the Jiangsu Science and Technology Press edition Grade 8 curriculum, the design incorporates experimental tasks that validate the theoretical notion of elastic force between objects. Four inquiry-based experimental modules are presented, alongside an analysis of the approach’s efficacy in cultivating key competencies, embracing progressive educational philosophies, and leveraging innovative technological tools.

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