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IMPROVING LOWER SECONDARY SCHOOL STUDENTS' KNOWLEDGE INTEGRATION OF BUOYANCY THROUGH ENHANCING THEIR UNDERSTANDING OF THE NATURE OF BUOYANCY

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Abstract. *In recent years, developing students' knowledge integration of specific topics through effective teaching methods has been a concern in science education. This study explored an alternative teaching method, which aims to help lower secondary school students develop their knowledge structure about buoyancy towards a logically integrated conceptual framework through enhancing their understanding of the nature of buoyancy. Specifically, this study constructed a conceptual framework on buoyancy and a set of matching test questions to map out the three levels of knowledge integration of students, and designed and implemented a teaching experiment of promoting students' understanding of the nature of buoyancy. Through quantitative and qualitative analysis, it was found that the knowledge integration development of the treatment group was significantly better than that of the control group. The results indicated that enhancing students' understanding of the nature of buoyancy can effectively improve their knowledge integration of buoyancy. Accordingly, improving knowledge integration through enhancing students' understanding of the nature of the specific scientific concept may be a new direction for future research.*

Keywords: *conceptual framework, knowledge integration of buoyancy, scientific concept understanding, the nature of buoyancy*

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Introduction

In recent years, cultivating students' ability to solve practical problems has been a main goal of science education (National Research Council, 2012; Nieminen et al., 2012). As for how to develop this ability, many studies have mentioned that it is necessary to help students establish reasonable connections among related scientific concepts and contextual features, leading to an integrated knowledge structure, so as they can obtain more effective reasoning pathways in solving problems (Dai et al., 2019; Liu et al., 2022). Therefore, it has been a concern in science education to seek effective teaching methods for improving students' knowledge integration about specific topics (Bao & Fritchman, 2021; Scalise, 2012). This study explored an alternative teaching method, which aims to improve students' knowledge integration about a specific concept topic through understanding the nature of the concept.

The concept topic of this study is buoyancy. As for why the topic of buoyancy was chosen, it is related to the personal experience of the first author of this study. The first author once worked as a science teacher in a lower secondary school in Zhejiang Province, China. When he taught the topic of buoyancy, he found that it was generally difficult for students to construct an integrated knowledge structure about buoyancy. At the same time, there seems to be a deviation in the definition of buoyancy in general science teaching in China, which greatly hinders students from correctly understanding the nature of buoyancy, and this may be the main reason why students are unable to effectively construct an integrated knowledge structure about buoyancy. In other words, understanding the nature of buoyancy may be the key to realize an integrated knowledge structure about buoyancy. This study was a verification of this hypothesis.

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The following were the two main aims of this study: (1) establish a conceptual framework and a set of matching test questions on the topic of buoyancy to map out students' different levels of knowledge integration of buoyancy; (2) design and implement a teaching experiment of promoting students' understanding of the nature of buoyancy, and verify its effect on students' knowledge integration of buoyancy.

Literature Review

Knowledge Integration in Science Education

In science education, there is a commonly accepted viewpoint that students' problem-solving performance on a certain topic depends on the knowledge structure they have constructed (Gerace et al., 2001; Snyder, 2000). For expert students, they have already established a complete conceptual framework, which contains relevant knowledge elements such as ideas, conceptions, principles, equations, contextual variables, etc., and these elements are meaningfully connected through some reasoning pathways (Bao & Fritchman, 2021; Eylon & Reif, 1984). From this perspective, the reason why expert students excel in solving related problems is that the contextual characteristics will activate their conceptual framework, and then some reasoning pathways will emerge as the strategies to solve the problems (Dai et al., 2019; Xie et al., 2021). On the contrary, novice students' knowledge structure is relatively fragmented. Although it also contains some knowledge elements, they are mechanically memorized, loose and unorganized (Eylon & Reif, 1984; Gerace et al., 2001). When novice students solve problems, they tend to directly match contextual characteristics with knowledge elements in memory, without a meaningful reasoning process, such as directly substituting contextual variables into relevant formulas for calculation. Once direct matching is not feasible, they have no alternative problem-solving strategies (Bao & Fritchman, 2021; Dai et al., 2019).

Accordingly, the critical way to enhance students' problem-solving ability lies in helping them construct a more integrated knowledge structure for the specific topic, and characterizing students' knowledge structure with an ideal conceptual framework is the necessary groundwork. In this regard, it is worth noting that individual cognitive characteristics may vary, and each topic may involve diverse knowledge elements and reasoning pathways. This means that the ideal conceptual framework should not be unique, and the appropriateness should be the principle in its construction (Dai et al., 2019; Xu et al., 2020).

Determining a central idea is the first and key step in the construction of a conceptual framework (Dai et al., 2019; Kubsch et al., 2018). The central idea has strong capacity for attracting other knowledge elements, like an anchor point that can be connected with other knowledge elements through specific logical relationships, leading to an integrated conceptual framework (Xie et al., 2021; Xu et al., 2020). The established conceptual framework can not only guide the implementation of teaching activities, driving students to construct this conceptual framework, but also serve as a basis for designing assessment instruments, analyzing students' development of this conceptual framework (Dai et al., 2019; Xie et al., 2021).

Student Learning of Buoyancy

The sinking and floating of objects in liquid is a very common life phenomenon for students, but buoyancy is a relatively difficult scientific concept for them (Radovanovic, 2012; Wagner et al., 2013). Relevant studies have found that students make many mistakes in learning buoyancy, some of which are caused by their daily experiences, such as the block of wood floats and the block of iron sinks because the latter is heavier, emerging objects are subject to buoyancy while sinking objects are not subject to buoyancy, and so on (Tomo, 2021; Wagner et al., 2013). From these mistakes, it can be seen that students need to go beyond the relevant daily experience to correctly understand buoyancy.

This fact is consistent with some descriptions of the characteristics of understanding scientific concepts, that is, understanding scientific concepts is not as intuitive and self explanatory as understanding daily concepts, but often requires an abstract thinking process of metaphor and modeling (Asakle & Barak, 2020; White & Frederikson, 2009). Unfortunately, the general teaching of buoyancy does not seem to be well aware of this key point. Taking the general teaching of buoyancy in China as an example, the definition of buoyancy is generally introduced from the perspective of daily experience, that is, "The force that the object immersed in the liquid is lifted vertically by the liquid is called buoyancy." And the teachers usually simply explain the definition of buoyancy based on students' relevant daily experience, and then verify the existence of this vertical force through a simple experiment (Hang

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a heavy object on the spring scale, and then immerse it in the liquid. It can be observed that the indication of the spring scale decreases.) (Gao et al., 2020; Shen et al., 2015). Next, the teachers will lead the students to learn other contents related to buoyancy.

However, previous studies have shown that the general teaching like the one mentioned above leads to students being unable to understand the nature of buoyancy and establish reasonable relationships among buoyancy and relevant knowledge elements such as variables, principles, equations, and so on (Minogue & Borland, 2016; Paik et al., 2017). Students tend to mechanically rely on the matching patterns in memory when solving buoyancy related problems. As a result, many students perform well on simple and familiar problems, but poorly on complex and unfamiliar problems (Kim & Paik, 2021; Young & Meredith, 2017).

Recognizing these shortcomings, researchers began to explore corresponding solutions. Some studies pointed out that the learning of buoyancy involves too many knowledge elements that students cannot handle simultaneously, so we need to help students find a certain effective way to integrate them (Minogue & Borland, 2016; Paik et al., 2017). Further studies on this topic have confirmed the potential significance and effectiveness of understanding the nature of buoyancy in integrating knowledge elements. The explanations of buoyancy related phenomena and the solutions to buoyancy related problems are truly correct only on the basis of considering the nature of buoyancy, which refers to the fact that buoyancy is an effect force exerted on the surfaces of an immersed object, resulting from the liquid gravity (Kim & Paik, 2021; Lima & Monteiro, 2013).

The Conceptual Framework and Assessment Questions for Mapping Out Students' Knowledge Integration in Learning of Buoyancy

The Conceptual Framework

Based on the above discussions, the nature of buoyancy was selected as the central idea. Then, we invited 3 professors of science education and 2 well-experienced science teachers to form an expert group to construct an appropriate conceptual framework through consultation.

Firstly, the expert group also believed that the nature of buoyancy is that buoyancy is an effect force exerted on the surfaces of an immersed object, resulting from the gravity of a liquid. Therefore, the accurate definition of buoyancy should be "The net force exerted by liquid pressures on the surfaces of an immersed object" (Kim & Paik, 2021; Lima & Monteiro, 2013). Chinese lower secondary school students are taking an elementary science curriculum, so this study only considered the net force in the vertical direction. As for the motion state of an immersed object in the vertical direction, it is determined by the buoyancy together with other forces acting on it vertically. Accordingly, the expert group pointed out that, on the basis of understanding the nature of buoyancy, students may perform the forces analysis of the immersed object according to its motion state, thus obtaining some equations for calculating buoyancy. In general, there are five motion states when an object immersed in a liquid partially or completely: emerged, suspended, sunk, emerging, sinking. The emerged, suspended and sunk objects are all in equilibrium vertically, with the difference that the buoyancy on the emerged or suspended object is equal to its gravity, while the sum of buoyancy and support force on the sunk object is equal to its gravity according to the forces synthesis principle and two forces balance principle. Accordingly, the equations $F_b = mg$ and $F_b = mg - F_s$ are available for buoyancy related calculations (The F_s in the equation refers to the container's support force for the object. And in science course of Chinese lower secondary school, the space between the bottom of the container and the object is assumed to be filled with liquid.). Conversely, the emerging or sinking object is not in equilibrium, for which the principle of two forces balance no longer applies. The basis for solving relevant problems is the Archimedes principle, that is, the buoyancy of an immersed object is numerically equal to the displaced liquid gravity, expressed by the equation $F_b = \rho g v$. The Archimedes principle is a reflection of the nature of buoyancy on the level of mathematical relationship. In the absence of an immersed object, the corresponding volume would be occupied by a liquid whose gravity would be supported by the rest of the liquid (Kubsch et al., 2018; Young & Meredith, 2017). From this point of view, the Archimedes principle applies to the immersed objects in all five motion states mentioned above.

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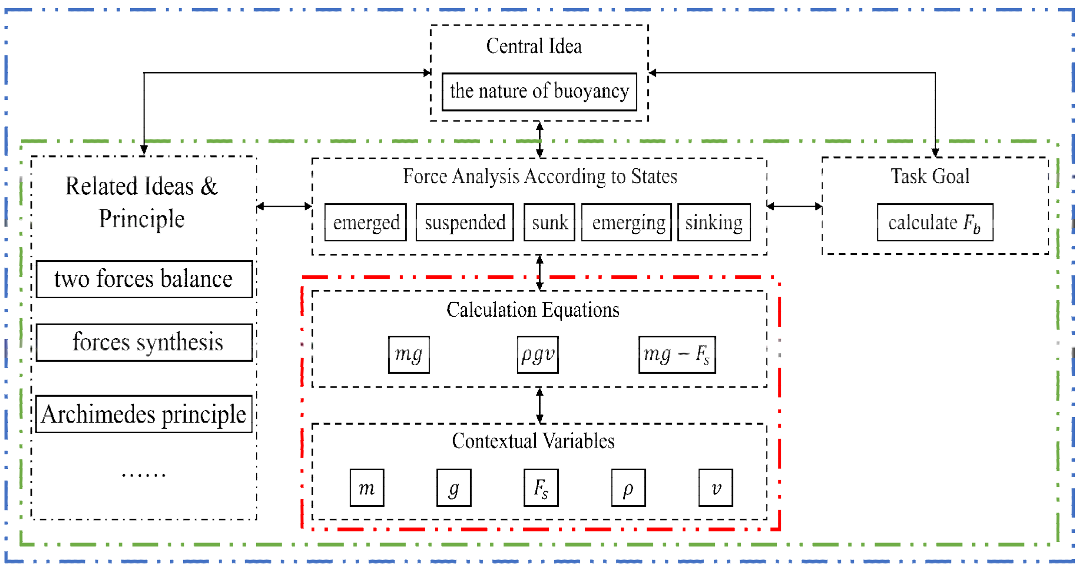
Figure 1
Conceptual Framework of Buoyancy



Based on the above discussion, this study established a conceptual framework of buoyancy, which can express a logically integrated knowledge structure of students in learning of buoyancy (As shown in Figure 1). And according to the representative knowledge elements and reasoning pathways of the conceptual framework, the expert group believes that students' knowledge integration of buoyancy can be roughly divided into three levels:

Low level: The best situation for students at this level is that they have constructed a mechanical connection between the calculation equations and the contextual variables (See the red dotted box in Figure 1). For example, when the mass of the immersed object, the acceleration of gravity, and the support force are directly given, students can mechanically substitute these variables into the equation $F_b = mg - F_s$ to calculate the buoyancy. However, when any of these three variables is not given in the problem, they will have no solution strategy except guessing.

Intermediate level: Students at intermediate level can integrate more knowledge elements (See the green dotted box in Figure 1). The difference between them and the low level students is that they can understand the reasoning pathways among the calculation equations, the motion states, and the related ideas & principles. For example, when an object is emerging, these students can infer that other equations are no longer valid and turn to the Archimedes principle. If the required variables are not provided directly, they can obtain these variables through logical reasoning from other relevant information. However, in the case of the object sticking to the container, these students will be baffled because they have not understood the nature of buoyancy.

High level: Students at this level have understood the nature of buoyancy, and driven by this understanding basis, they have established a well-integrated conceptual framework of buoyancy (See the blue dotted box in Figure 1). When solving buoyancy related problems, no matter which contextual variables are given, these students have a great chance of success to come up with solutions based on complex connections between knowledge elements.

The Assessment Questions

According to the constructed conceptual framework and the division of students' knowledge integration, a test consisting of 12 single-choice questions (1/4) was designed to assess students' different knowledge integration of buoyancy (The single-choice question (1/4) is one of the most common assessment methods in Chinese

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lower secondary schools). These 12 questions were all derived from the questions that students often encounter in their daily study, removing the complex calculations and the irrelevant information. According to the degree of knowledge integration, these questions can be divided into three sets: single set, multilink set, and integrated set.

Q3, Q5, and Q8 belong to the single set, which only involves the application of the contextual variables and the calculation equations. To obtain the correct answer, students only need to insert the given variables into the corresponding equations. For example, Q3 provides all the required variables required for the equation $F_b = \rho g v$.

Q1, Q4, Q10, and Q11 belong to the multilink set, which also need to be solved by using one of the three equations. However, the variables of the equations are not directly given, but can be obtained by connecting the relevant ideas & principles and the correct reasoning pathways. For example, Q4 gives the motion state of a complex system whose total gravity can be calculated indirectly and then can be solved with the equation $F_b = mg$.

Q2, Q6, Q7, Q9, and Q12 belong to the integrated set, which can be solved when students have understood the nature of buoyancy and formed an integrated conceptual framework. The situational characteristics of these questions are relatively complex and unfamiliar to students, for example, the situation of Q6 is that the object is trapped in mud. Understanding the nature of buoyancy is a prerequisite for solving these questions, and then the corresponding reasoning pathways selected and applied on this basis can be fitting.

It was expected that all students can answer most of single questions after learning the buoyancy courses, unless they use the wrong equations or make calculation mistakes. Most intermediate and high level students can answer most of multilink questions. Only the high level students can maintain excellent performance in integrated questions.

The reliability of this test has been verified in another study (Zou et al., 2022). This study was used to analyze the effect of understanding the nature of buoyancy on corresponding knowledge integration after the teaching experiment. The detailed test questions are attached in the attachment.

Research Methodology

Background

On the basis of constructing the conceptual framework and assessment questions for mapping out students' knowledge integration in learning of buoyancy, this study designed intervention lessons to enhance students' understanding of the nature of buoyancy. In September 2022, a total of 163 students participated in the teaching experiment, of which 80 students received intervention lessons as the treatment group, and the remaining 83 students received general lessons as the control group. Before and after the buoyancy lessons, all 163 students participated in the pre-test and post-test, and some of them continued to participate in further interviews. Then, various quantitative and qualitative analysis methods were applied to explore the effect of the intervention lessons on students' knowledge integration.

Participants

The participants consisted of 163 8th grade students (14-15 years) in four classes, with 79 boys and 84 girls, who were all from a lower secondary school located in a midsize city (Jinhua, Zhejiang) in China. Before learning buoyancy, they had learned the relevant concepts and principles involved in the conceptual framework. 83 students in two classes were randomly selected as the control group to receive 4 general lessons of buoyancy, and 80 students in the other two classes served as the treatment group to receive 4 newly designed lessons that emphasize understanding the nature of buoyancy.

Design and Implementation of the Intervention Lessons

The general lessons for the control group students. The general teaching of buoyancy in Chinese lower secondary schools consisted of four 45-minute lessons. In the initial lesson, with the teacher's help, students perceived the existence of buoyancy from the perspective of daily experience and understood that the upward force produced by water or other liquids on an immersed object is called buoyancy.

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In the second lesson, under the guidance of the teacher, students recognized the five possible motion states of immersed objects and analyzed the forces on objects in different motion states, and then derived two equations, $F_b = mg$, and $F_b = mg - F_s$ according to the three different equilibrium states (emerged, suspended, sunk).

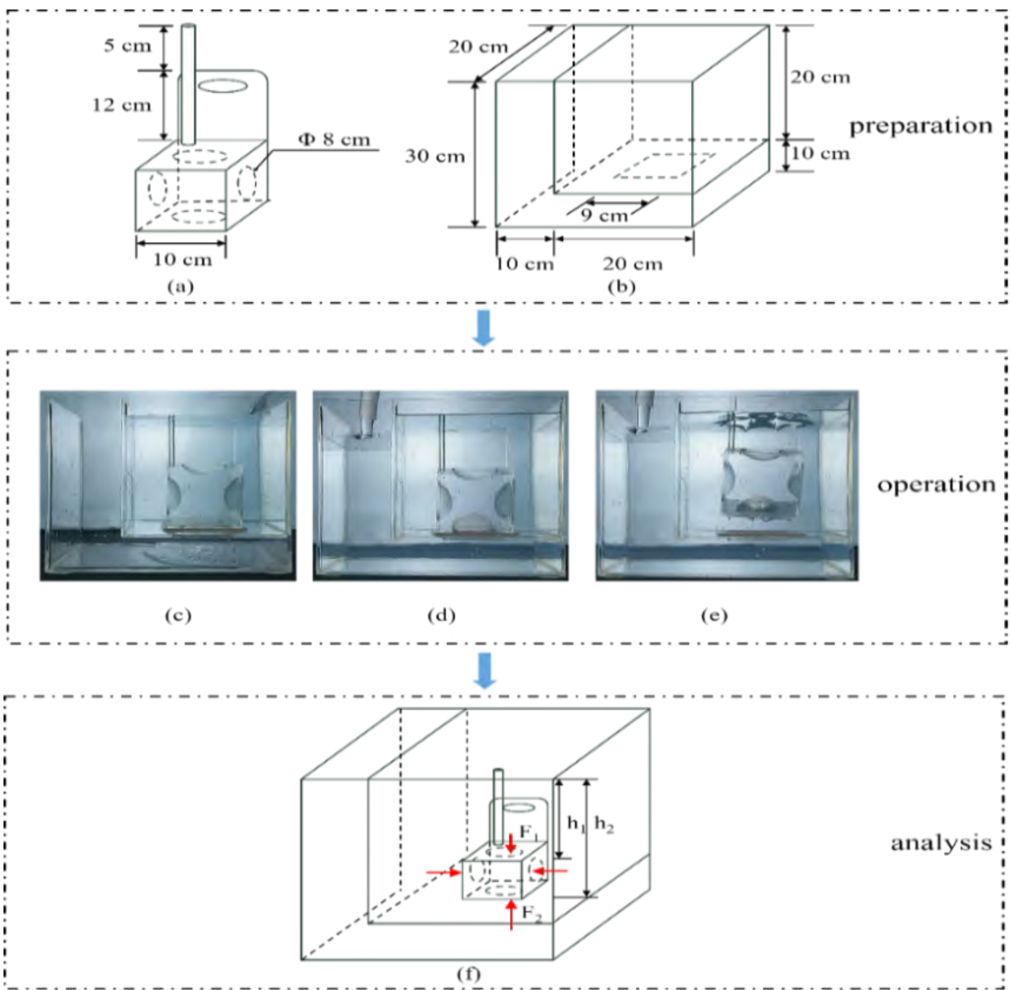
In the third lesson, students experimentally investigated the relationship between the magnitude of buoyancy and the amount of the displaced water, and generalized their conclusions to other liquids, so as to get the Archimedes principle and the corresponding equation $F_b = \rho g v$.

In the last lesson, students were trained in real and typical question situations such as densitometers, ships, and submarines, reinforcing mechanical connections between various variables and above three equations.

The 83 students of the control group attended the four general buoyancy lessons. In general, these lessons spent no time on explaining the nature of buoyancy, but focused on the derivation of the three equations and the application of them in specific situations.

The intervention lessons for the students in the treatment group. The 80 students of the treatment group attended 4 newly designed 45-minute lessons that emphasize understanding the nature of buoyancy. In the initial lesson, the teacher guided students to understand the nature of buoyancy through a newly designed experiment, and come up with the improved definition of buoyancy. The experiment mainly was newly designed based on the idea of visualizing the nature of buoyancy (Amedeo et al, 2015; Moreira et al., 2013).

Figure 2
The Newly Designed Experiment



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Firstly, the teacher prepared a cube device as shown in Figure 2(a) and a water container with a double-layer sink as shown in Figure 2(b). Then, the teacher explained to the students as follows: (1) Each surface of the cube device has a prototype rubber membrane to show the pressure effect of the liquid. (2) And the bottom of the inner layer of the container has a square gap, when the cube device is placed on the inner layer of the container, the pressure of the water of the outer layer will act on the rubber membrane at the bottom of the cube device through this gap. (3) With the increase of the water of the outer layer, the pressure will become bigger and bigger, and the deformation of the rubber membrane on the bottom of the cube device will become larger and larger until the cube device appears to float up.

Secondly, the teacher put the cube device on the inner layer of the container, and then added water to the inner layer until the water exceeded the upper surface of the cube device for a certain distance. In this process, it can be observed that the rubber membrane on the left and right surfaces of the cube device first appeared larger and larger deformation. Since the water exceeded the upper surface of the cube device, the rubber membrane on the upper surface of the cube device also began to deform, and the degree of deformation was increasing. Meanwhile, the rubber membrane on the lower surface of the cube device has never been deformed.

Thirdly, the teacher started to add water to the outer layer of the container. Since the water reached the gap, the rubber membrane on the bottom of the cube device began to deform, and the degree of deformation increased with the increase of the outer water until the cube device appeared to float up (Figure 2(c), 2(d), 2(e)).

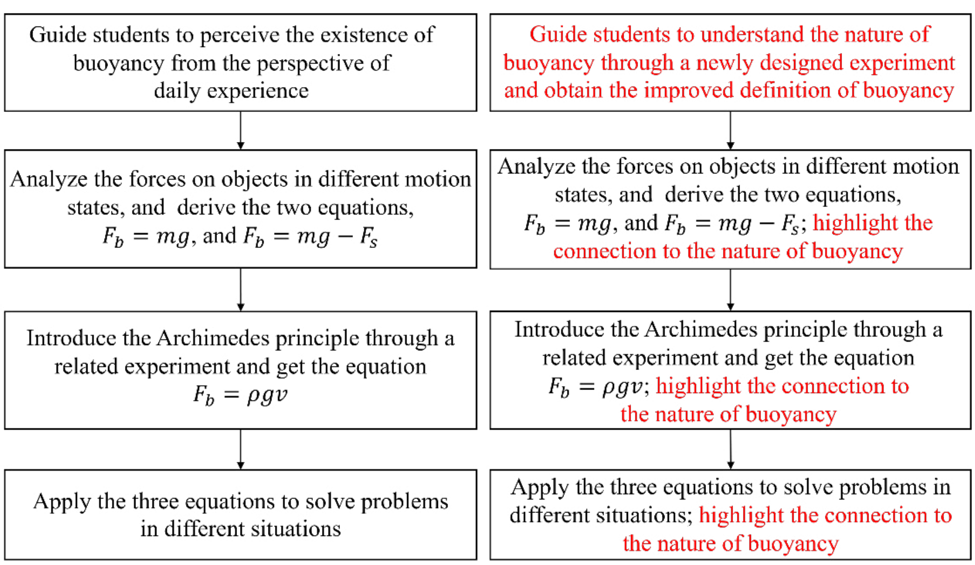
Finally, in combination with the above experimental process, the teacher guided the students to analyze the forces on the cube device as shown in Figure 2(f) to help students understand the nature and source of buoyancy, and defined buoyancy as "The net force of an immersed object exerted by liquid pressures on the surfaces.".

The contents of the next three lessons were similar to those of the control group, but in every lesson, the teacher highlighted the connection between the contents and the nature of buoyancy.

The general lessons and the intervention lessons are summarized as shown in Figure 3. All lessons were taught within one week by an outstanding science teacher recognized by the school, who had not taught these students before.

Figure 3

The General Lessons and the Intervention Lessons



(a) general lessons (b) intervention lessons

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Data Collection and Analysis

Both control and treatment groups took the pre-test and post-test before and after the lessons. Each test was completed in 30 minutes. Students' pre-test and post-test performances were compared by two-way ANOVA, and further explored by T-test, so that the effectiveness of the intervention lessons can be judged. The score distribution for the different question sets was analyzed to reveal the difference of the development characteristics of students' knowledge structure. At the same time, exploratory factor analysis (EFA) was performed on the post-test data to explore the impact of the intervention lessons on students' knowledge integration.

Additionally, a random sample of 30 students from each group participated in the think-out-loud interviews to illustrate their reasoning process of problem solving, so as to reveal their knowledge structure in greater depth after receiving the lessons. The interview of each participant took approximately 20 minutes and was recorded. The authors transcribed and sorted the same interview recordings into a preliminary interview text respectively, and finally formed a formal interview text for analysis after full discussion. To avoid the subjectivity of researchers affecting the objectivity of the analysis process, the authors analyzed the same interview data respectively, and explored different opinions through discussion and negotiation until the analysis results achieved refinement and agreement.

Research Results

Quantitative Analysis on Students' Knowledge Integration Development

The overview of the pre-test and post-test performances of the parallel groups is given in Figure 4. The pre-test data points of the two groups are almost coincident, which means these students were statistically identical in terms of conceptual understanding level ahead of the lessons. This is further confirmed by the results of ANOVA [$F(2, 483) = .151$, $p = .860$], which illustrate that there was no statistically significant interaction between different groups and question sets on the initial diagnostic test.

As shown in Figure 4(a), the overall performances of the two groups of students have improved after the implementation of the buoyancy lessons, but the degree of improvement is significantly different [$t_{treatment}(79) = 17.091$, $p < .001$, $d = 1.910$; $t_{control}(82) = 9.262$, $p < .001$, $d = 1.016$]. This demonstrates that the intervention lessons had a more positive effect on conceptual learning of buoyancy than the general lessons. In addition, the post-test ANOVA reveals significant interaction [$F(2,483) = 5.269$, $p = .005$], with main effects for both question sets [$F(12,483) = 43.026$, $p < .001$] and teaching conditions [$F(1,483) = 52.758$, $p < .001$]. Accordingly, the intervention lessons had different degrees of effects on students with regard to different question sets. As shown in Figure 4(b) (c) (d), for the integrated set, the advancement of the treatment group students' performances is far superior to that of the control group [$t_{treatment}(79) = 15.411$, $p < .001$, $d = 1.722$; $t_{control}(82) = 7.057$, $p < .001$, $d = 0.774$]. With regard to the multilink set, the difference between the two groups is narrower [$t_{treatment}(79) = 12.888$, $p < .001$, $d = 1.441$; $t_{control}(82) = 6.611$, $p < .001$, $d = 0.7256$]. And the difference is further narrower for the single set [$t_{treatment}(79) = 11.338$, $p < .001$, $d = 1.267$; $t_{control}(82) = 6.546$, $p < .001$, $d = 0.7185$]. These results manifest that the intervention lessons can help students understand the nature of buoyancy and form an integrated knowledge structure more effectively because, with the upgrading of the question set, students were required more to understand the nature of buoyancy and establish an integrated knowledge structure.

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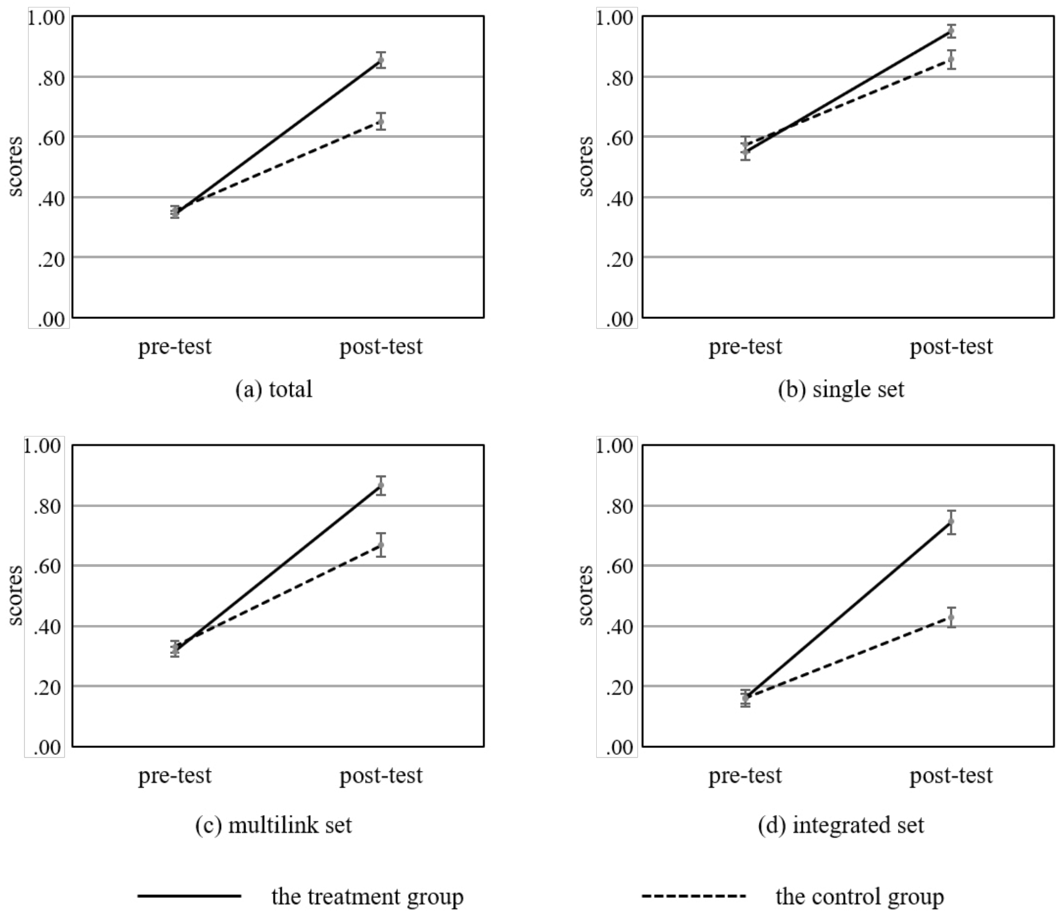
Figure 4

Pre-post Testing Performances of Students From the Two Groups



To explore the difference of the development characteristics of students' knowledge structure about buoyancy, the distribution of scores for the different question sets was analyzed (see Figure 5). The students of the control group and the treatment group were further assigned to five crowds respectively according to their ranking of total scores in the post-test, each containing 20% of the group sample. As shown in Figure 5, the development trend of the scores between the control group students and the treatment students is similar. Specifically, for both groups, students' scores on the integrated set are lower than the scores on the simple set and the multilink set for all crowds, except for those who get full marks. And for both groups, with the increase of students' total scores, their scores on any question set also increase, and the trend of their performance gaps between any two question sets is similar. These results reveal a similar general progression in the two group students' development of knowledge structure about buoyancy. However, the growth rate of the treatment group students' scores on each question set is significantly faster than that of the control group, indicating that the intervention lessons had a statistically significant effect on the development of students' knowledge structure in learning of buoyancy.

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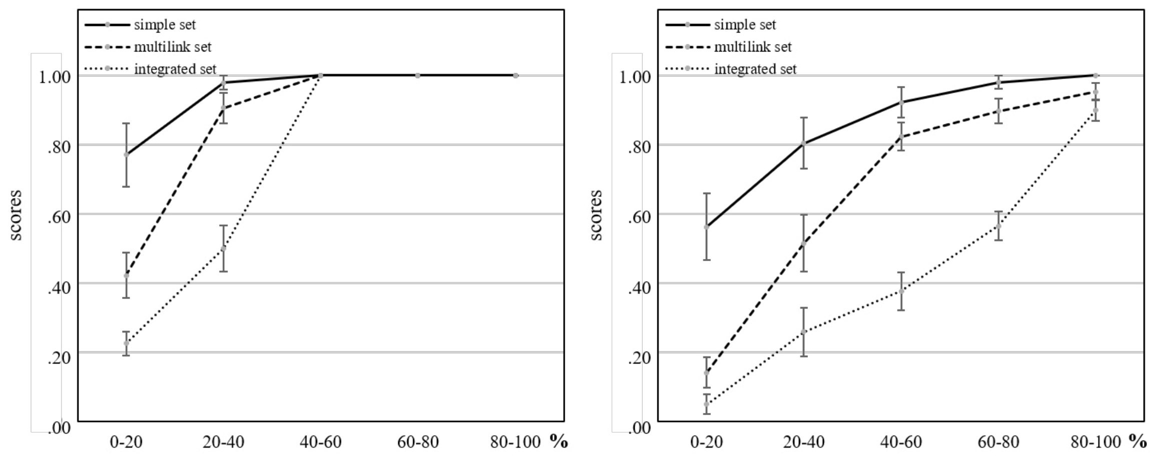
Figure 5
The Scores Distribution for Different Question Sets of Different Overall Performances



The results of exploratory factor analysis (EFA) are plotted in Figure 6, providing detailed information for further analysis of students' knowledge structure after the implementation of the buoyancy lessons. For the treatment group, the first eigenvalue explains nearly half (47.101%) of the variance, indicating that the single factor can explain students' performances on different questions (See Figure 6(a) for the factor loading of the questions). This means that these students have established a relatively integrated knowledge structure about buoyancy on the whole. For the control group, three common factors with eigenvalues greater than 1 are extracted, which explain 21%, 20%, and 17% of the total variance, respectively, and their cumulative variance contribution is 58%. As shown in Figure 6(b), the plot of factor loading indicates that the three factors exactly represent the above-mentioned three question sets, factors 1, 2, 3 correspond to single set, multilink set, integrated set, respectively. And there is little correlation between the single set and multilink set (.412), between the single set and integrated set (.210) and between the multilink set and integrated set (.221). It can also be seen that control group students' responses on the single questions and the multilink questions have a moderate correlation (.412), but their responses on the single questions (.210) and the multilink questions (.221) are less connected to the integrated questions. These results represent that the knowledge structure of control group students was relatively unintegrated on the whole and lacked an understanding of the nature of buoyancy. Comparing the analysis results of the two groups, the knowledge integration of treatment group students was significantly better than that of control group students. It can be concluded that the intervention lessons of emphasizing understanding the nature of buoyancy had a statistically significant effect on students' knowledge integration of buoyancy.

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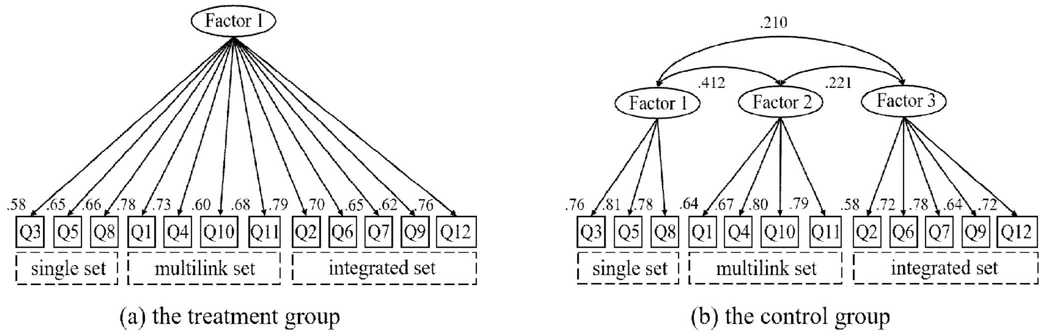
Figure 6
Factor Loadings for EFA of Students' Post-test Data



Qualitative Analysis on Students' Reasoning Process

Among 163 students, 60 students were randomly selected as the subjects of think-out-loud interviews to externalize the thought process when solving problems. Through the analysis of the interview results, their knowledge integration about buoyancy can be roughly divided into three levels, which is consistent with the previous division.

Low Level: Students at this level can only mechanically link the equations in memory to the variables in context without a meaningful reasoning process. In other words, these students' knowledge structure was at a preliminary level. They neither understood the nature of buoyancy nor knew the relationships among relevant ideas & principles. For instance, student 1 and student 2 scored well in the single questions, but they performed poorly on the multilink questions and integrated questions.

Student 1: (For question 2) "The question gives the displaced liquid volume and the object mass. This confused me. Should I use the equation $F_b = \rho g v$ or the equation $F_b = mg$? Then, I used $F_b = \rho g v$ randomly."

Student 2: (For question 12) "In question 12, the object is stuck to the bottom of the container, so I wanted to use $F_b = mg - F_s$. But I was surprised to find that the given variables were inconsistent to this equation. Finally, I had to guess one option."

As student 1 mentioned, he tried to substitute the known variables directly into the equation $F_b = \rho g v$ and $F_b = mg$, but either equation would fail because there is no buoyancy in outer space in the absence of gravity. Similarly, student 2 selected the equation $F_b = mg - F_s$ based on the motion state of the object, but the information given in the question is incomplete for the equation. Actually, since the object is stuck to the container's bottom, that is, there is no liquid between the bottom of the container and the object, the object only receives a downward force from the liquid according to the nature of buoyancy. It can be seen from the responses of these two students that their knowledge structure was less integrated, which only contained the contextual variables, the relevant equations and the simple relationship between them. As a result, the direct pattern matching became the solitary problem-solving strategy for these students.

Intermediate Level: These students can not only establish the relationships between contextual variables and the equations, but also make connections to related ideas & principles. However, students at this level still cannot effectively understand and apply the nature of buoyancy.

Student 3: (For question 6) "The object is trapped in the mud at the container's bottom, the equation $F_b = mg - F_s$ should be used. However, the buoyancy seems to be downward here, it's impossible. I was confused about this question. " (For question 2) "I tried to solve this question by applying equation $F_b = mg$ or $F_b = \rho g v$, but I found that the two answers were different, I was so confused."

Student 4: (For question 9) "At the beginning, this object is stationary at the container's bottom, $F_b = mg - F_s$, so options A and B are incorrect. And then, the object is emerging, $F_b \neq mg$, so option C is wrong. It's D." (A is actually the correct answer.)

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Student 3 and student 4 were able to recall the related calculation equations and obtain the required variables through connecting the corresponding analysis processes, which drove them to solve most of the single questions and the multilink questions smoothly. However, the intermediate level students' accuracy in integrated questions was still low due to the lack of understanding of the nature of buoyancy. For question 6, since the object is sunk into the mud, it is only necessary to consider the downward pressure from the liquid on the object's upper surface. For question 9, it is also necessary to analyze the upward and downward pressure on the object respectively to get the answer. Therefore, the knowledge structure of these students at intermediate level should establish more logical connections around the nature of buoyancy to get more efficient solutions to problems. In terms of this, these students still had the characteristics of pattern matching when solving problems, but they have mastered more relevant patterns than the low level students.

High Level: Students at this level have developed a deep understanding of the nature of buoyancy and a highly integrated knowledge structure. In other words, in the knowledge structure of these students, the contextual variables, the calculation equations, the related ideas & principles, and the central idea, were not isolated from each other, but logically connected. Therefore, these students were able to answer almost all questions correctly.

Student 5: (For question 2) "The source of buoyancy is the liquid gravity, but the liquids in outer space are not affected by gravity, so the correct answer of this question is zero, because the $g = 0$."

Student 6: (For question 7) "The buoyancy is caused by the liquid gravity, and it is equal to the net force on the object's upper and lower surfaces. The object is in equilibrium, so the answer can be obtained through analyzing the forces on the object. After calculation, I got option D."

It can be clearly seen that these students considered the nature of buoyancy first when solving the related problems, and then comprehensively applied calculation equations, contextual variables, and related ideas & principles to solve the problem. As a result, these students performed better on all questions, especially on the integrated questions.

The number and percentage at each level of the 60 interviewed students are shown in Table 1. This further corroborates the findings of quantitative analysis: Compared with the general lessons, the newly designed intervention lessons can help students understand the nature of buoyancy and establish an integrated knowledge structure more effectively.

Table 1
The Number and Percentage at Each Level of the 60 Interviewed Students

Group	Total	Knowledge integration level (N(%))		
		Low	Intermediate	High
Treatment Group	30	4(13.4)	13(43.3)	13(43.3)
Control Group	30	13(43.3)	9(30.0)	8(26.7)

Discussion

This study developed an alternative teaching method that aims to improve lower secondary school students' understanding of the nature of buoyancy and help them develop their knowledge structure of buoyancy into a logically integrated conceptual framework. Above all, it should be pointed out objectively that there are still a few limitations with this study. Firstly, this study was conducted in China, so the general applicability of the research findings to a broader context needs to be further verified. Secondly, the sample size of this study is relatively small, and the confidence of the outcomes needs to be further improved through a larger sample size in future studies. Despite these limitations, this study has made some significant contributions, which are discussed as follows:

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Buoyancy is a Difficult Concept to Understand for Students

Consistent with the findings of previous studies, the findings of this study also showed that buoyancy is indeed a difficult concept to understand for students (Kim & Paik, 2021; Wagner et al., 2013; Radovanovic, 2012). Although students' performances on different question sets have improved significantly after the implementation of the buoyancy lessons, the degrees of improvement are not ideal. For the students of the control group, their knowledge structure is fragmented as a whole, and more than 70% of them are still at the low level or the intermediate level of knowledge integration, who barely understand the nature of buoyancy. For the students of the treatment group, their knowledge structure is integrated as a whole, but about 43% of them have not reached a high level of knowledge integration, and need to further deepen their understanding of the nature of buoyancy. Meanwhile, it can be seen from the students' specific descriptions of their reasoning processes that most students rely on pattern matching to solve problems, which leads that they can only deal with relatively typical and familiar problems. Therefore, targeted cognitive diagnosis and teaching methods are needed to help students better understand buoyancy.

The General Teaching of Buoyancy is not Conducive to Students' Knowledge Integration

In the general teaching of buoyancy in China, the definition of buoyancy does not really reveal the nature of buoyancy. What's more, all the general buoyancy lessons mainly focus on helping students get familiar with the solution patterns of buoyancy related problems, rather than helping students establish the integrated knowledge structure. As in other research, under the influence of the general teaching, students in this study cannot effectively construct logical correlations and reasoning pathways among buoyancy related knowledge elements, and they depend on mechanical matching rather than meaningful reasoning when faced with relevant problems (Minogue & Borland, 2016; Tomo, 2021). Accordingly, the general teaching of buoyancy is only conducive to students' familiarity with relevant problem situations and problem-solving patterns, but is not conducive to students' knowledge integration, leading them to often encounter troubles in the face of complex and unfamiliar contexts. In view of this, it is necessary to explore some new teaching approaches that contribute to knowledge integration.

The Teaching of Emphasizing the Nature of Buoyancy is Effective for Students' Knowledge Integration

This study constructed a conceptual framework of buoyancy through a series of logical relationships to diagnose students' knowledge integration of buoyancy. At the same time, this study designed and implemented 4 new buoyancy lessons of emphasizing understanding the nature of buoyancy. The results of data analysis showed that understanding the nature has a significant effect on students' forming an integrated knowledge structure of buoyancy. Although this conclusion is consistent with previous relevant research studies, this study has made new progress in presenting students' cognitive schematics and teaching method design of helping students understand the nature of buoyancy (Gao et al., 2020; Paik et al., 2017; Zou et al., 2022). Therefore, more teaching methods that can help students understand the nature of buoyancy, as well as more logical conceptual frameworks about buoyancy, should be sought to help students better understand the nature of buoyancy and develop a more comprehensive knowledge integration of buoyancy.

Conclusions and Implications

Overall, this study has confirmed that the method of constructing a conceptual framework on buoyancy and a set of matching test questions is effective in mapping out lower-secondary school students' different conceptual understanding in learning buoyancy. Meanwhile, this study designed and implemented an effective teaching method to develop students' knowledge integration of buoyancy through enhancing their understanding of the nature of buoyancy. The experiment result indicated that the knowledge integration development of the treatment group students was significantly better than that of the control group students, and the treatment group had significantly more students who reached the intermediate and high levels than the control group.

These results verified the effectiveness of understanding the nature of buoyancy in improving knowledge integration about buoyancy, which may bring a new approach to knowledge integration research in science education, that is, to enhance students' knowledge integration about a specific concept topic by guiding students

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to understand the nature of the concept. Of course, the adaptability of this approach needs to be further tested through subsequent research studies on more topics. On the other hand, for the research and practice of buoyancy teaching in China, this study is absolutely groundbreaking. Specifically, this study found that Chinese general teaching of buoyancy has a biased definition of buoyancy and the characteristics of attaching importance to the problem-solving pattern training, and provided a set of detailed reference strategies for targeted improvement.

Declaration of Interest

The authors declare no competing interest.

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Ethics statement

This study was approved by the Zhejiang Normal University Review Board. Informed consent was obtained for all participants.

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Appendix

The Assessment Questions Used in This Study

(Tips: if gravity acceleration and water density are involved in the question, g is taken as 10N / kg, and water density is taken as 1.0×10^{3} kg/m^3; and in all cases that involve the object is sunk, unless otherwise specified, it is considered that the space between the bottom of the object and the bottom of the container is filled with liquid.)

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1. When an object is placed on the desktop, the supporting force of the desktop to it is 40N. When the object is put into the water, it is sunk and receives 30N supporting force from the bottom of the container. Please calculate the buoyancy of this object in the water. (B)

A.5 N B.10 N C.30 N D.40 N

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2. In outer space, if we put a small ball with a volume of 3×10^{-6} m^3 and a mass of 2 g into a cup with water, it would be suspended. What is the buoyancy of this small ball in the water? (A)

A.0 N B.0.01 N C.0.02 N D.0.03 N

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3. If we gently put an object into a cup full with water, 80 ml of water would overflow from the cup. Please calculate the buoyancy of this object in the water. (A)

A.0.8 N B.1.8 N C.2.8 N D.3.8 N

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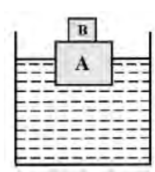
4. As shown in the figure, there is an appropriate amount of water in the container. If we place the wooden block A with a gravity of 5N in the container and press the wooden block B with a gravity of 3N on wooden block A, wooden block A would emerge on the water with wooden block B. What is the buoyancy of wooden block A in the water at this time? (C)

A.3 N B.5 N C.8 N D.10 N



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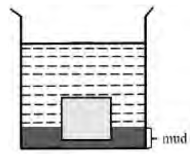
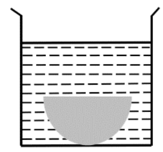
5. James puts a small ball with a mass of 0.04kg into a container with water, and the state of it in the water emerges. Please calculate the buoyancy of this ball in the water. (D)
A.0.1 N B.0.2 N C.0.3 N D.0.4 N

6. As shown in the figure, the object with a volume of 600cm^3 and a gravity of 3N is sunk into the mud at the bottom of the container. It is known that the volume of the object trapped in the mud is 200cm^3, the total embedding force of the mud on it is 7 N, and the force exerted by the water pressures on the upper surface of the object is 5N. If we want to salvage the object out of the mud, how much force is needed at least? (D)
A.9 N B.10 N C.11 N D.15 N

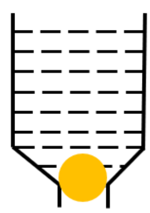


7. As shown in the figure, the hemispherical object with a volume of 700 cm^3 and a gravity of 4N is stationary at the bottom of a container with water. If we know that the force exerted by the water pressures on the upper surface of the object is 5N. What is the force exerted by the water pressures on the lower surface (spherical part) of the object? (D)
A.2 N B.4 N C.6 N D.8 N



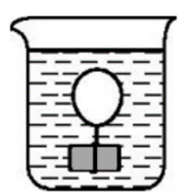
8. The gravity of the object is 7N. When we put the object into the water, it would sink and receive 6N supporting force from the bottom of the container. Please calculate the buoyancy of this object in the water. (A)
A.1 N B.6 N C.7 N D.13 N

9. Put the mouth of a lidless and bottomless beverage bottle facing downward, put the table tennis ball (the diameter is slightly larger than the diameter of the bottle mouth) into the bottle and inject water. You can see a small amount of water flowing out of the bottle's mouth. At this time, the table tennis ball is stationary still, and then block the bottle mouth with your hand. After a while, the table tennis ball will float up. Which of the following analysis is correct? (A)



A. the direction of the net force of liquid on the table tennis ball is vertical downward when it is stationary.
B. The supporting force of the table tennis ball in the figure is balanced with the gravity when it is stationary.
C. In the process of table tennis emerging, the buoyancy it receives is equal to the gravity it receives.
D. In the process of table tennis emerging, the buoyancy it receives remains unchanged.

10. As shown in the figure, the object is composed of a balloon and a stone (the stone is hung with the string under the balloon), and the object is suspended in the water. The mass of the stone is 0.4kg, the mass of the balloon is 0.1kg (including the air mass inside the balloon)and the mass of the string is 0.05kg. Please calculate the buoyancy of this object in the water. (A)
A.5.5 N B.5 N C.4 N D.1 N



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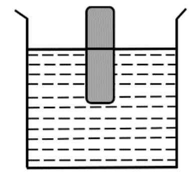
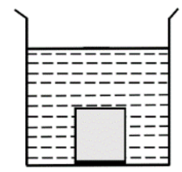
11. James puts the cuboid block with a total volume of 180 cm^3 into a container with water. When the block is stationary, the state of it in the water is emerged, and its volume above the water surface is 80cm^3. What is the buoyancy of the cuboid block in the water? (B)
A.0.8 N B.1 N C.1.8 N D.2 N



12. The cuboid block with a volume of 600cm^3 and a gravity of 3N is stuck to the bottom of the container, and there is no gap between the block bottom and the bottom of the pool. It is known that the viscous force on the object is 5N and the downward pressure on the upper surface of the object is 4N. If we want to salvage the object from the water, how much force is required at least? (B)
A.18 N B.12 N C.6 N D.3 N



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