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ASSESSMENT OF KNOWLEDGE INTEGRATION IN STUDENT LEARNING OF BUOYANT FORCE

Yi Zou,
Lizhen Jin,
Yanbing Li,
Tao Hu

Abstract. *Students' problem-solving ability depends on their understanding of related scientific concepts. Therefore, the modeling and assessment of students' understanding of specific scientific concepts is important to promote students' problem-solving ability, as it can find students' understanding difficulties and explore breakthrough strategies accordingly. Inspired by the theory of knowledge integration and combined with the situational characteristics of science education in China, this study established a conceptual framework about buoyant force, which was applied to model students' different understandings of it. And based on the established framework, an assessment of buoyant force was designed and tested among 622 Chinese lower-secondary school students. Through the analysis of the test data and the interview outcomes, it was found that students' understanding of buoyant force could be divided into three levels of knowledge integration including novice, intermediate, and expert. Furthermore, the results demonstrate that an emphasis on the nature of buoyant force can be an effective strategy to help students achieve a deeper conceptual understanding of buoyant force, leading to a more integrated knowledge structure.*

Keywords: *assessment of knowledge integration, buoyant force, central idea, conceptual framework, scientific concept understanding*

Yi Zou, Lizhen Jin
Zhejiang Normal University, China
Yanbing Li, Tao Hu
East China Normal University, China

Introduction

With the increasingly close relationship between science and social living, to develop students' ability to solve problems in real contexts has become the fundamental goal of science education (Murcia, 2009; National Research Council, 2008; Özdem, 2010). However, many students can successfully solve problems in typical and familiar contexts, but when they face problems in complex or unfamiliar contexts, they are often helpless (Alonso & Marcelo, 1992; Chiu et al., 2007; Kim & Pak, 2002). The reason for this phenomenon lies in the traditional instruction to a great extent, which has the characteristics of memorizing rules and formulas by rote (Bloom et al., 1956; Rivet & Krajcik, 2010). As a result, students develop a tendency to rely on pattern matching rather than concept understanding when solving problems.

Recognizing the weaknesses of students' understanding of scientific concepts and the shortcomings of the traditional instruction, many modeling and assessment studies have been explored to characterize and identify students' conceptual understanding on a specific topic, so that teachers can grasp students' learning difficulties and then adopt new targeted teaching methods to improve students' conceptual understanding on the topic (Bao & Fritchman, 2021; Demkanin, 2020; Demkanin et al., 2022; Gilbert & John, 2012; Linn, 2000; Scalise, 2012). Inspired by the theory of knowledge integration, this study explored an alternative modeling and assessment approach to clearly probe features of students' conceptual understanding in learning of buoyant force by establishing a conceptual framework and designing and implementing a test accordingly.

In perspective of knowledge integration, students' knowledge structure is the key factor to determine their problem-solving performance (Champagne et al., 1981; Chi et al., 1981; Gerace et al., 2001; Schoenfeld & Herrmann, 1982; Snyder, 2000). The knowledge structure about a specific

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topic of experts is a logically integrated conceptual framework, which connected the related ideas, conceptions, and contextual variables through certain reasoning pathways (Bao & Fritchman, 2021; Champagne et al., 1981; Chi et al., 1981; Eylon & Reif, 1984; Schoenfeld & Herrmann, 1982). Such a conceptual framework can be activated by contextual features when experts encounter problems, and then some specific strategic reasoning pathways emerge, which makes experts have a great probability to solve problems smoothly (Dai et al., 2019; Duit & Treagust, 2003; Nie et al., 2019; Xie et al., 2021; Xu et al., 2020). On the other hand, the knowledge structure about the same topic of novices is loose and lacking organization, which only contains some knowledge fragments such as calculation equations and related variables. When novices solve problems, they tend to focus on the variables in the context, and then directly match these variables with the equations in memory (Champagne et al., 1981; Chi et al., 1981; Eylon & Reif, 1984; Gerace et al., 2001; Schoenfeld & Herrmann, 1982). If the matching fails, they have no other strategies to solve the problems. In summary, helping students construct more integrated conceptual frameworks for the particular concept is the key to improve their problem-solving ability (Dai et al., 2019; Nie et al., 2019; Xie et al., 2021; Xu et al., 2020), and clearly presenting an ideal conceptual framework to analyze and assess the characteristics of students' knowledge structures is the basic and prerequisite work. Accordingly, the two goals of this study were: (1) Construct a conceptual framework on the topic of buoyant force from the visual angle of the knowledge integration and apply it to analyze students' understanding in learning buoyant force. (2) Employ an assessment based on the conceptual framework to test students' understanding statuses of buoyant force and make some inferences on their knowledge structures.

The Conceptual Framework of Buoyant Force

Informed by many existing knowledge integration studies, identifying a central idea is the most important step to build a conceptual framework for a specific concept (Dai et al., 2019; Kubsch et al., 2018; Nie et al., 2019; Xie et al., 2021; Xu et al., 2020). The central idea is like an anchor point with strong adsorption force, which can link other relevant ideas and conceptions according to certain logical relationships (Dai et al., 2019; Nie et al., 2019; Xie et al., 2021; Xu et al., 2020). Once a conceptual framework has been established, it can be used as a guidance to design and employ some assessment instruments to accurately map out students' conceptual understanding on a specific topic, as it provides core scientific principles and explanatory mechanisms on the topic (Bao & Fritchman, 2021; Dai et al., 2019; Nie et al., 2019; Xie et al., 2021; Xu et al., 2020). It should be noted that the choice of the central idea is not fixed, the form and structure of the conceptual framework can also be diversified, it mainly depends on the purpose and emphasis of the study and the views of experts in the field (Dai et al., 2019; Duit & Treagust, 2003; Nie et al., 2019; Xie et al., 2021; Xu et al., 2020). This study aimed to model and assess students' understanding of the concept of buoyant force, found out the difficulties, and provided empirical evidence for exploring the corresponding breakthrough strategies. Therefore, the selection of the central idea was carried out on the basis of reviewing the relevant studies on students' learning difficulties of buoyant force and sufficient expert consultation and demonstration.

The floating and sinking of an object is a common phenomenon in daily life, but students' understanding about buoyant force formed through daily experience often has many mistakes, such as big/heavy objects sink and small/light things float, hollow objects float and objects with air in them float, objects with holes sink (Besson, 2004; Kim & Kim, 2012; Libarkin et al., 2003; Loverude et al., 2003; Radovanović & Sliško, 2013; Smith et al., 1985; Suat, 2008; Tomo, 2021; Wagner et al., 2013; Yin et al., 2008). From these misconceptions, it can be seen that the concept of buoyant force seems to involve many variables, such as mass, weight, volume, shape, and so on. Some studies have pointed out that buoyant force is a difficult concept for students because it is closely related to too many other scientific concepts and principles, and students usually can't deal with too many knowledge elements at the same time unless they can integrate them in a certain effective way (Gao et al., 2020; Halford et al., 1986; Minogue & Borland, 2016; Mullet, 1988; Paik et al., 2017; Suat, 2008; Yin et al., 2014). In this regard, many studies have shown that understanding the nature of buoyant force may be such an effective way (Loverude et al., 2003; Paik et al., 2017; Young & Meredith, 2017). In other words, the most important thing in learning about the buoyant force is to understand its essential meaning, that is, the buoyant force is an effect force, which is caused by the effect of liquid gravity on the surfaces of an immersed object (Kim & Paik, 2021; Lima & Monteiro, 2013). With this understanding basis, the interpretation of buoyant force related phenomena and the solution of buoyant force related problems

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are correct (Paik et al., 2017; Radovanovic, 2012; Young & Meredith, 2017).

The above findings of literature review were consistent with the results of expert consultation and demonstration. Most of the experts who participated in this study mentioned that the biggest difficulty for students in learning buoyant force is that they cannot completely understand the definition of the buoyant force, which is usually expressed as "the net force exerted by liquid pressures on the surface of an object" or simply as "$F_b = \Delta F$" (Kim & Paik, 2021; Lima & Monteiro, 2013). In fact, this definition not only reflects a mathematical relationship, but also contains the nature of buoyant force, when problems related to buoyant force need to be solved, the most important thing is to understand that the buoyant force is an effect force, which is caused by the gravity acting on the liquid. Based on the above studies' review and the expert opinions, this study finally selected the nature of the buoyant force as the central idea and expressed it as "NoB" for convenience of expression.

After identifying the central idea, this study continued to construct the conceptual framework of buoyant force through expert consultation and demonstration. Since buoyant force is an effect force, it can be compared with other forces on the object in the vertical direction (the Chinese students participating in this study have only taken introductory level courses, so the net force only considers which in the vertical direction here.). Such force analysis can be linked with the motion state of the object in the liquid, so as to form a series of reasoning pathways to solve buoyant force related problems. When an object is partially or completely immersed in a liquid, it will appear in five states in the vertical direction: emerged, suspended, sunk, emerging, sinking. For the case of the object is emerged or suspended, which shows that the object is in equilibrium, the equation $F_b = mg$ can be obtained according to the principle of two force balance. In terms of the object is sunk, which also shows that the object is in equilibrium, the equation $F_b = mg\text{-}Fs$ can be obtained according to the principle of two force balance and the principle of force synthesis (In science education in China, unless otherwise specified, it is usually assumed that the space between the bottom of the object and the bottom of the container is filled with liquid.). The Fs represents the support force of the bottom of the container to the object. In the case where the object is emerging or sinking, it is no longer in equilibrium, so the force analysis of the object from the perspective of balance force is no longer effective. At the time, we need to turn our attention to the Archimedes principle, which asserts that the buoyant force of an object immersed in a liquid is equal to the gravity of the displaced liquid (Kim & Paik, 2021; Lima & Monteiro, 2013; Minogue & Borland, 2016; Young & Meredith, 2017). Imaging without the object, the same immersed space will be occupied by the same volume of liquid, the weight of those liquid is supported by other parts of the liquid. Therefore, when an object is emerging or sinking, the buoyant force can be calculated by the formula $F_b = \rho gv$. Of course, this formula is also applicable to the case that the object is emerged, suspended, or sunk.

This study was conducted among Chinese students. Based on the above discussion and careful review of the course content of buoyant force theme, a conceptual framework was established as shown in Figure 1. The top component is the central idea, which expresses the nature of buoyant force. When solving buoyant force related problems, experts often have formed a basic understanding that buoyant force is an effect force, which together with other forces in the vertical direction determines the state of an object in liquid. Then, they begin to analyze the forces acting upon the object according to its state. If the object is emerged or suspended, they will calculate the buoyant force by applying $F_b = mg$ according to the principle of two force balance. If the object is sunk, they will calculate the buoyant force by applying $F_b = mg\text{-}Fs$ according to the principle of two force balance and the principle of force synthesis. If the object is emerging or sinking, they will calculate the buoyant force by applying $F_b = \rho gv$ according to the Archimedes principle. What's more, in the process of state judgment and forces analysis, experts will always call to mind that $F_b = \rho gv$ is applicable to any of the above situations to deal with the contexts where the gravity and the support force acting on the object cannot be obtained.

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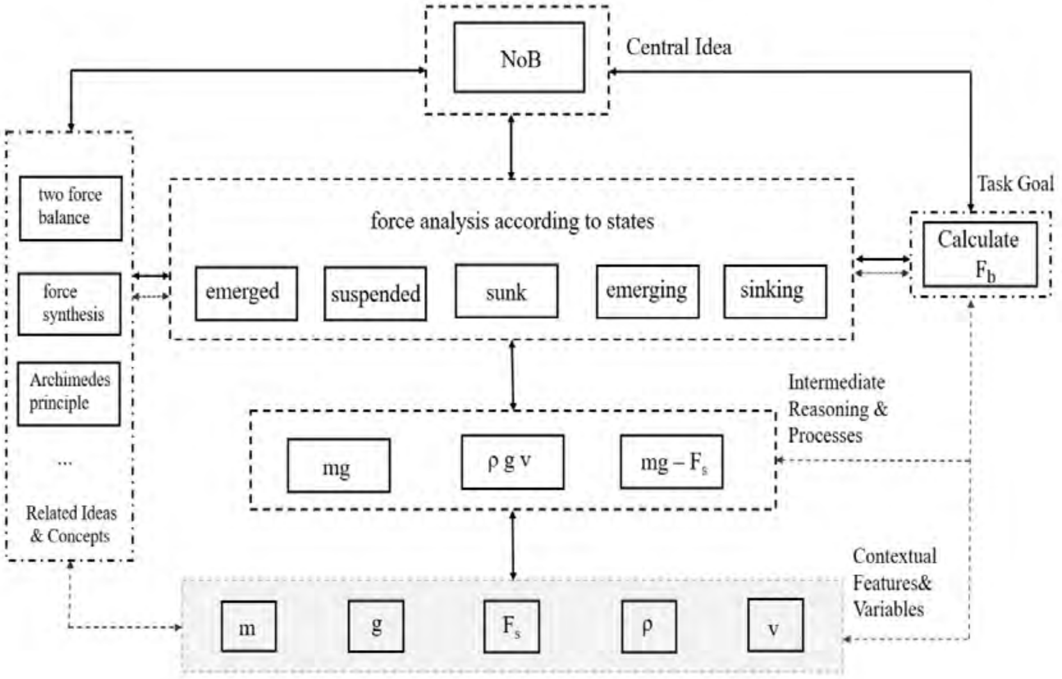
Figure 1
Conceptual Framework of Buoyant Force



The middle layer includes different buoyant force calculation equations obtained after analysis of the states and forces of the object in liquid. The reasoning process also shows that the central idea is closely tied to some other scientific concepts and principles, such as two force balance principle, force synthesis principle and Archimedes principle. These correlative components are listed in "related concepts & principles" in Figure 1. The bottom layer involves the contextual variables directly corresponding to the calculation equations of buoyant force, such as mass, gravitational acceleration, density of liquid, volume of the displaced liquid, and Fs. As to great majority problems related to buoyant force, the task goal is usually to calculate the buoyant force or needs to be achieved by calculating buoyant force, as shown in the box on the right in Figure 1.

Different components of the conceptual framework are linked by numerous arrows. The solid arrows represent the reasoning pathways of experts on solving buoyant force related problems. These all pass through the central idea and link to other components, forming a well-integrated knowledge structure. Meanwhile, the dashed arrows tend to ignore the central idea, and make weak connections between the different components. These indicate that the novices' knowledge structure is fragmented, mechanical memory and matching contextual variables with equations are their habitual behaviors when solving problems. The arrows in Figure 1 are two-way arrows. This means that a link can be originated from either side. It is also possible that some students have only constructed one direction link between certain components. These students can be considered at certain stages between novice level and expert level.

Modeling Student Understanding Using the Conceptual Framework

According to the representative pathways of the conceptual framework shown in Figure 1, this study divided students' understanding of buoyant force and their ability to solve related problems into three levels:

1) Novice level: This is the lowest level of understanding of buoyant force. Students at this level either have low cognitive functions, often miss information, and activate wrong knowledge in solving problems related to buoyant force, or at best have established direct relations between the buoyant force calculation equations and the contextual variables (the components of bottom layer). For instance, when given density of liquid, gravitational acceleration, and volume of the displaced liquid, these students

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at best can only use $F_b = \rho gv$ to calculate the buoyant force mechanically. But they will be baffled when any of these three context variables is not provided in the problem.

2) Intermediate level: Students at this level can connect the contextual variables with the middle layer components. They have more strategies and better performance than novices in calculating buoyant force, especially in applying the relevant concepts and principles to obtain the unknown variables, but they still don't understand the essential meaning of buoyant force. As an example, students at this level can judge that the object sunk at the bottom of a container is in equilibrium, then use $F_b = mg\text{-}Fs$ accordingly. When the variables involved in these equations are not directly given in the problem, they can also obtain these required variables by analyzing relevant information and applying correct reasoning pathways. But when the object sticks to the container, they still tend to use $F_b = mg\text{-}Fs$ to calculate the buoyant force. For the sake of establishing some more effective problem-solving methods, these students need to have a deeper understanding of the central idea to make their knowledge structures more integrated.
3) Expert level: This is the highest level of understanding of buoyant force. Students at this level have formed a well-integrated knowledge structure, which drives them to connect the contextual variables with the central idea, as well as many of the related concepts, principles, and the intermediate reasoning pathways. When solving problems, these students have a greater chance of success, because they can follow through the related connections all the way to the nature of buoyant force with any given contextual variables, then get the effective problem-solving strategies according to some specific reasoning pathways.

Under the guidance of the constructed conceptual framework and the discussions above, a single-choice assessment was developed to probe the characteristics of students' knowledge structures of buoyant force. Furthermore, this study explored students' thinking processes and reasoning pathways through follow-up interviews.

Research Methodology

Design of the Buoyant Force Test

Based on the constructed conceptual framework, a test consists of 12 single-choice questions (there are 4 options for each question) was designed to assess students' understanding of buoyant force. All the 12 questions were adapted from the ones commonly used in instruction. For each question, tried to simplify the calculation involved and avoid information irrelevant to the conceptual framework. The questions were designed into 3 sets with varying degrees of knowledge connectedness and contextual familiarity, including single-link familiar question set, multilink familiar question set, and integrated-link unfamiliar question set.

The single-link familiar set contains 3 questions (Q3, Q5, Q8) that the students often encounter in their daily learning, which can be solved by directly using one of the following three equations: $F_b = mg$, $F_b = mg\text{-}Fs$, $F_b = \rho gv$. In these questions, the contextual variables such as m, g, Fs, ρ, v are given directly, students can directly match them with the equations to reach the conclusions. It was expected that expert and intermediate level students can successfully answer most of these questions, and so can novice students, unless they forget the questions or make calculation errors.

The multilink familiar set includes 4 questions (Q1, Q4, Q10, Q11) that the students often encounter too, but these questions all require multiple steps to correctly obtain the contextual variables by connecting the related concepts & principles and the intermediate reasoning & processes in order to get the answers. For example, Q1 asks the students to first analyze the gravity of an object, and then use the equation $F_b = mg\text{-}Fs$ to get the result. It was expected that in responding to these questions the students at expert level should be capable of answering all of them correctly, the students at intermediate level should often be able to answer a large fraction of them correctly. Meanwhile, the students at novice level can't succeed in obtaining proper answers under normal circumstances.

The integrated-link unfamiliar set contains 5 questions (Q2, Q6, Q7, Q9, Q12). These questions were designed to evaluate whether students can successfully apply the central idea in relatively unfamiliar problems. In other words, to answer these questions correctly, students need to understand the essential meaning of buoyant force and be capable of applying it in unfamiliar contexts successfully, which include contexts such as the object in outer space, the object sticks to the bottom of container, the object be sunk into the mud, and so on. It was expected

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that when answering these questions, students at different levels may perform differently. The students at novice level almost need to guess, so they may not answer any questions correctly. The students at intermediate level should also have difficulty with these questions but may succeed in some of them. Meanwhile, the students at expert level should be able to solve most of these questions by applying the central idea.

The test questions and the predictive performance of students with different levels of knowledge integration on these questions can be summarized as shown in Table 1.

Table 1
Assessment Questions Used in this Study

Knowledge integration	Single-link familiar	Multilink familiar	Integrated-link unfamiliar
	Q3,Q5,Q8	Q1,Q4,Q10,Q11	Q2,Q6,Q7,Q9,Q12
Novice level	Occasionally successful	Rarely successful	Guessing
Intermediate level	Mostly successful	Often successful	Sometimes successful
Expert level	Always successful	Always successful	Mostly successful

Research Procedure

The participants of this study were 622 8th grade students taking an introductory level science course, who were from a lower-secondary school in Jinhua City, Zhejiang Province, China. Jinhua is a moderately developed city in China, and this lower-secondary school is at the medium quality level in Jinhua. The average age of these students was 13.6 years old, including 333 girls and 289 boys. And 402 of these students were from 10 ordinary classes and the remaining 220 students were from 6 better classes. The academic performance of students from ordinary classes was different from that of students from better classes, because they were divided in different types of classes according to their entrance grades. The difference of students' academic performance was acceptable, and even the main basis for the selection of participants in this study, which was more conducive to acquire the ideal study results, that was, students would show different levels of understanding on buoyant force. All the 622 students took the test in December 2021 within 40 minutes. From September 2021 to October 2021, these students had learned about buoyant force in their science courses. The teaching content and strategies of buoyant force adopted by the science teachers of these students were similar (see Figure 8 in Appendix).

After the test, a variety of quantitative and qualitative methods were applied to explore and verify the students' conceptual understanding of buoyant force. In order to determine the assessment structures related to the different question sets, exploratory factor analysis (EFA) was carried out on students' test data. Statistical significances of comparisons between class level (the better class vs the ordinary class) and question set were determined with two-way ANOVA and further explored through student t tests. The size of differences among different question sets were measured with Cohen's *d* effect sizes. Additionally, 48 of the 622 students who participated in the test were randomly selected to continue to attend think-out-loud interviews. They were required to explicate the reasoning process when dealing with questions in detail, so that their knowledge structures could be interpreted more deeply. Each interview lasted for about 30 minutes and was audiotaped.

Research Results

Quantitative Study on Students' Knowledge Structure Development

Firstly, an exploratory factor analysis (EFA) was conducted on all students' test data. It is a scree plot of the EFA eigenvalues as shown in Figure 2. The results show that there are three factors with eigenvalues greater than 1, which explain 49% of the cumulative variance (i.e., 18%, 16%, and 15% for factors 1, 2 and 3, respectively). And Figure 3 provides the factor loading of all the questions on these three factors.

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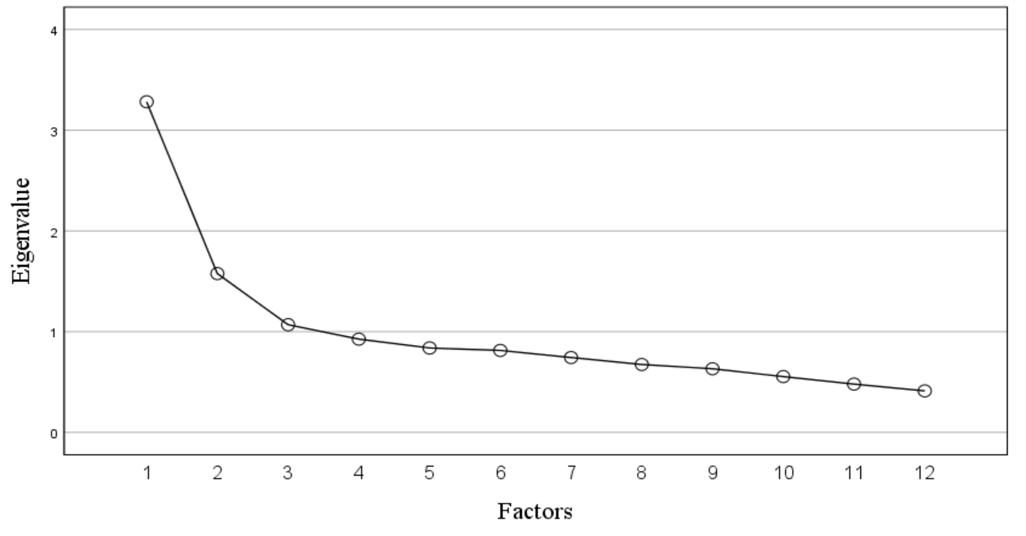
Figure 2
Scree Plot of EFA Eigenvalues of All Students' Test Data



The assessment test contains three categories that properly match the design of the three question sets, which was confirmed in the EFA result. As shown in Figure 3, factor 1 represents single-link familiar question set, factor 2 represents multilink familiar question set, and factor 3 represents the integrated-link unfamiliar question set. The results also show that students' responses on the single-link familiar question set are moderately correlated to their responses on multilink familiar question set (.429). However, the students' proficiency in solving the single-link familiar question set (.244) and the multilink familiar question set (.221) is less connected to the integrated-link unfamiliar question set. It may represent a less integrated (or more fragmented) knowledge structure, especially the lack of a deep understanding of the central idea.

Figure 3
Factor Loadings for EFA of All Students' Test with Three-Factor Solution

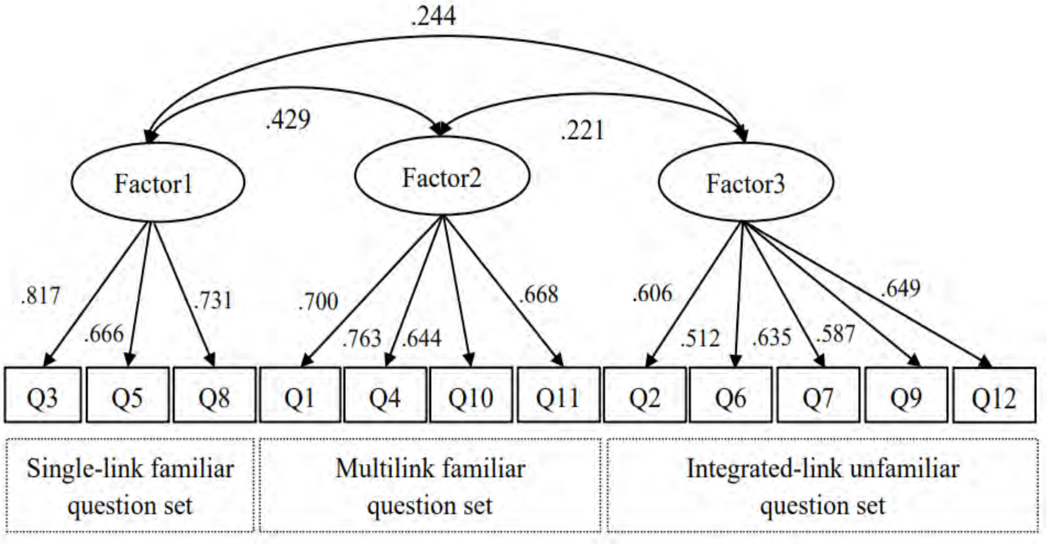


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Figure 4 shows the performance of students in better classes and ordinary classes across the different question sets. And the details are listed in Table 2. Performance differences between class levels were compared using two-way ANOVA (class level and question set). The main effects of class level ($F(1, 1860) = 157.163$, $p < .001$, $\eta^2p = .078$) and question set ($F(1, 1860) = 533.980$, $p < .001$, $\eta^2p = .365$) were measured. The influence of the question set is shown in Table 2 below. We can see that whether in the better class or in the ordinary class, students perform best in the single-link familiar question set and worst in the integrated-link unfamiliar question set, which are consistent with the expectations shown in Table 1. From the above analysis results, it can be seen that the question design shown in Table 1 can distinguish the scores of students with a high level of statistical significance. Directly comparing performances for each class level reveals students in better class with higher scores than students in the ordinary class, both within each question set ($t_{(S)}(620) = 6.719$, $p< .001$, $d = .563$), ($t_{(M)}(620) = 6.640$, $p< .001$, $d = .557$), ($t_{(I)}(620) = 8.431$, $p < .001$, $d = .707$) and overall ($t(218) = 10.378$, $p < .001$, $d = .870$). The differences can be predicted because students in different classes have different levels of academic performance. However, the relative performance of the two classes at different levels on the different question sets is quite similar (two almost parallel trend lines as shown in Figure 4). The results of analysis of ANOVA also confirmed this, indicating that there is no significant interaction between class level and question set ($F(2, 1860) = 2.636$, $p < .072$, $\eta^2p = .003$).

Figure 4
Students' Performance across Different Question Sets

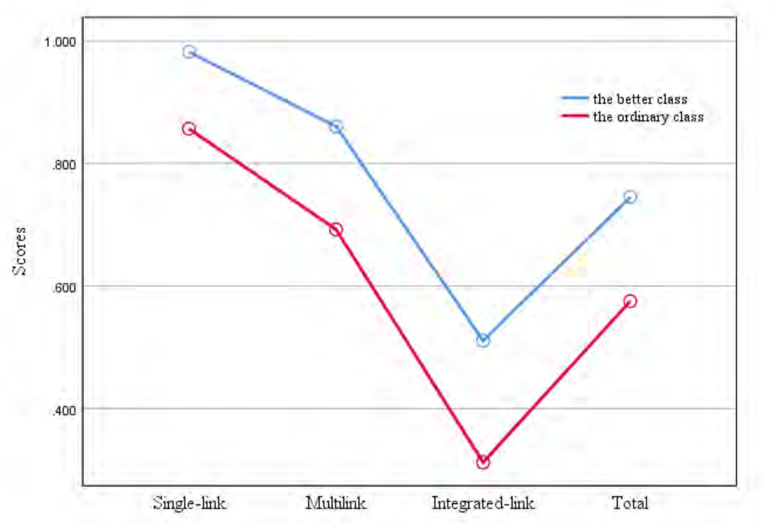

Table 2
Summary of Students' Performance in Different Question Sets at Different Levels of Classes, and Comparison of T-Test Results of Two Groups of Students

Question set	Better class		Ordinary class			
	M	*SE*	*M*	*SE*	*t*	*d*
Single-link familiar	.982	.005	.857	.014	6.719***	.563
Multilink familiar	.860	.017	.692	.016	6.640***	.557
Integrated-link unfamiliar	.511	.021	.313	.013	8.431***	.707
Total	.745	.012	.575	.010	10.378*	.870

Notes: *$p < .05$, ***$p < .001$; *SE*: the standard deviation of a sampling distribution.

In order to research the different responses of students with different overall performance levels in the three question sets, the students were assigned to five performance groups, each containing 20% of the total sample. The

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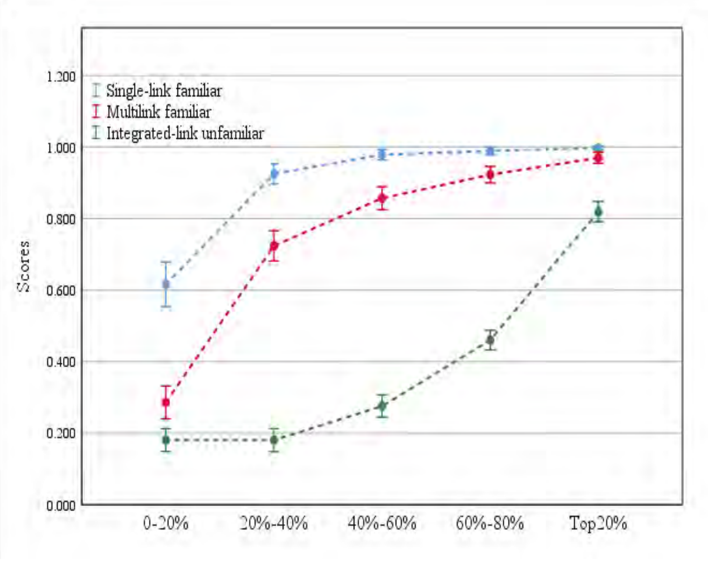
performance level was determined by the students' scores in the test, which reflect their overall learning results of buoyant force. As shown in Figure 5, the scores on integrated-link unfamiliar question set are consistently below the scores on multilink familiar question set and single-link familiar question set for all groups.

The students with low total scores (<20%) can successfully answer most of these questions on single-link familiar question set but fail to obtain correct answers on multilink familiar question set and integrated-link unfamiliar question set. This is not different from the expected performances of novice students listed in Table 1. With the increase of the total score, performance gaps between the integrated-link unfamiliar question set and the other two question sets are more pronounced, but the performance gap between single-link familiar question set and multilink familiar question set is closing, indicating that students in this range have begun to perform well on simple and more complex typical questions using memorization but without establishing a deep understanding. With the further improvement of the total score, performance gaps between the different question sets are less pronounced, indicating that students have developed partially integrated knowledge structures that allow them to achieve occasional success in some unfamiliar situations. At last, students with the highest scores (>80%) have formed a well-integrated knowledge structure, which drives them perform well in three question sets. These results reveal a general progression of student knowledge integration, which is very consistent with the discussion in Table 1.

Figure 5

Students' Scores in Different Question Sets. The Error Bars Represent Standard Error



The knowledge structures of expert-level students were further explored using exploratory factor analysis (EFA), constructed the correlation matrix of all project scores, and calculated the eigenvalues. As shown in Figure 6, it is a scree plot of the EFA eigenvalues. The results show that the first eigenvalue can explain nearly 64% the variance. This indicates that students' performance can be fully explained by a single salient factor, which means a quite integrated knowledge structure (See Figure 7 for the loading of all the questions on the single factor). When compared to the knowledge structure of the all students, which has three distinctive factors, this merging effect further indicates that these expert-level students have formed a well-integrated knowledge structure. Considering the meaning of analyzing these students' data is controversial because they got most of the questions correct, the characteristics of their knowledge structure need to be further interpreted in combination with the subsequent qualitative analysis.

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Figure 6
Scree Plot of EFA Eigenvalues of High-Level Students' Test Data

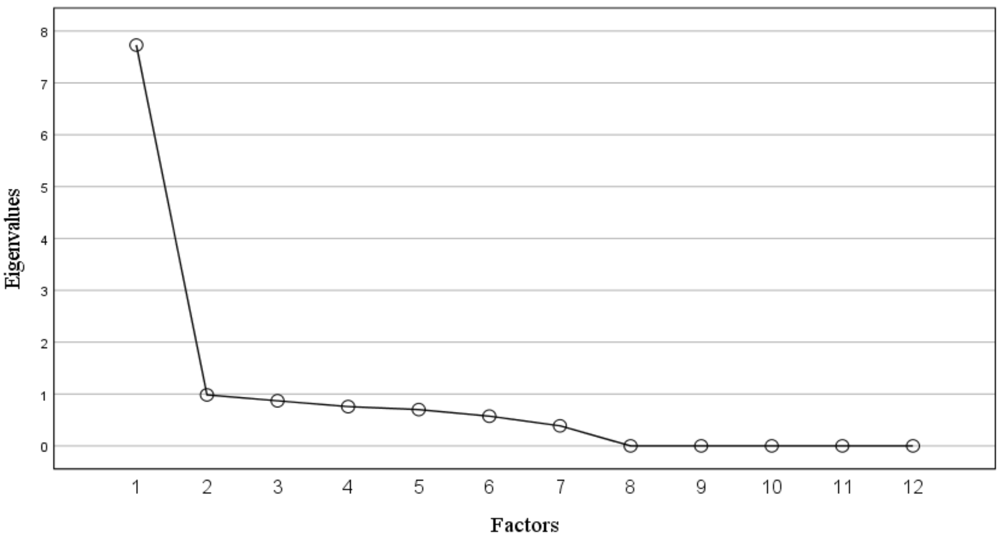
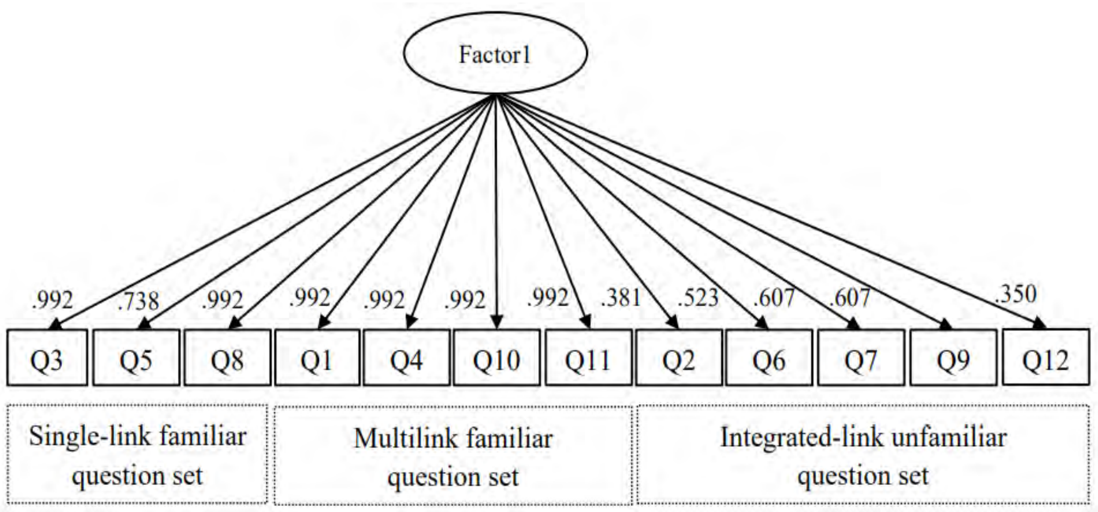


Figure 7
Factor Loadings for EFA of High-Level Students' Test with one Factor



Summarizing these results and combining with the discussion in Table 1, students at the three levels of knowledge integration perform differently on questions with differing degrees of knowledge connectedness and contextual familiarity. Since the average total score of the test can be used as a serviceable indicator of the different knowledge integration levels, it is proposed to divide the scores of 0% - 20%, 20% - 80% and 80% - 100% as the novice-intermediate-expert levels of knowledge integration, which is summarized in Table 3.

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Table 3

Summary of Total Score and Question Set Score of Each Knowledge Integration Level Based on Test Data. Standard Errors are Given in Parentheses.

Knowledge integration level	*N*	Single-link typical	Multilink typical	Integrated-link atypical
Novice	125	.616(.017)	.286(.017)	.181(.017)
Intermediate	372	.964(.010)	.834(.010)	.305(.010)
Expert	125	.997(.017)	.970(.017)	.819(.017)

Notes: standard error is the standard deviation of a sampling distribution.

The assessment results have reflected that the intermediate level of knowledge integration is the state that most students were in, where they have more strategies and better performance than novices in calculating buoyant force, but they still rarely succeed in the integrated-link unfamiliar questions. This clearly shows that most students lack a well-integrated knowledge structure and understanding of the nature of buoyant force. In response to this issue, it is critical to helping students construct conceptual frameworks for particular concepts to promote their knowledge integration level and improve their problem-solving ability.

Qualitative Study on Students' Reasoning Process

48 of the 622 students were randomly selected to participate in think-out-loud interviews to ascertain the possible reasoning pathways and knowledge structures. According to students' responses, three different levels of students' understanding were determined and described below.

Novice level: These students can only link the contextual variables directly to related equations in their memory without meaningful reasoning processes, and often lose information or activate not proper knowledge. It can be seen that the knowledge structure of these students is largely fragmented, which is not only not connected with the essential meaning of buoyant force, but also with the relevant concepts and principles. Therefore, novices are able to correctly solve a limited number of simple familiar questions using memorized equations. The following are excerpts from interviews with students who exhibit this level of problem-solving behavior:

Student A: *(Response to question 1) "In this question, the object is sunk at the bottom of the container, well, the equation seems to be F_b = mg-Fs, right? I remember there should be this equation. But the gravity of the object is unknown here, so I directly consider the buoyant force here is equal to Fs." (Response to question 2) "I really didn't know how to solve the question. This is the case in outer space, the question gives both the mass of the object and the volume of the displaced liquid, I didn't know whether to use the equation F_b=mg or F_b =ρgv. Finally, I randomly chose F_b =ρgv."*

Student B: *(Response to question 12) "I've never seen such a question. The object is stuck to the bottom of the container, is this the same as when it is sunk at the bottom of the container? Should I use the equation F_b=mg-Fs, right? But the variables in the question do not correspond to this equation, So I just guess an answer."*

Both student A and student B answered most of the questions in single-link familiar set, but they did badly in multilink familiar set and integrated-link unfamiliar set. As student A mentioned, the context that the object is sunk at the bottom of the container prompted him to recall the equation F_b = mg-Fs. However, when he found that the gravity of the object was not given in the question, he created a new equation F_b = Fs to calculate the buoyant force incorrectly. This thinking process shows that the student only remembered some equations of buoyant force. The same is true for student A in question 2. He only thought of the corresponding equations F_b = mg and F_b = ρgv according to the mass and the volume given in the question, but the correct solution to this question should consider that the liquid will not produce buoyant force on the object, because the liquid is not affected by gravity in outer space.

Meanwhile, student B recalled the equation F_b = mg-Fs cued by the context that the object is stuck to the bottom of container. Then, the student attempted to seek out all the required variables in the question to solve for the answer. Unfortunately, the variables given in this question were not gravity and support force, then, the

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student didn't know how to solve it and can only guess one answer. In fact, students need to apply the central idea, that is, the essential meaning of buoyant force, and then get answer by calculating the force difference between the upper and lower surfaces of the object in this question.

The performances the two students demonstrated here support the viewpoint that novices' knowledge structure is decentralized with simple connections between contextual variables and related equations, leading them to rely on pattern matching as the main strategy to solve problems.

Intermediate level: These students can make sufficient connections between contextual variables and related concepts and principles but have great difficulties in understanding and applying the central idea. They seem to predominantly pay attention to how to get the variables involved in the equations by connecting related concepts and principles, and then they can use the equations to calculate the buoyant force. But when the solution of the problem requires students to understand the nature of buoyant force, they often feel confused. For instance, student C successfully solved all the questions in multilink familiar set but had trouble with the questions in integrated-link unfamiliar set.

Student C: *(Response to question 6) "I can't make sure the answer of this question. The object is sunk into the mud at the bottom of the container, I think I should use the equation $F_b = mg-Fs$, I remembered that Fs is always upward, but it seems to be downward here. If I still use this equation to calculate the buoyant force, the direction of the buoyant force seems to be downward, but we all know that the direction of buoyant force should be upward." (Response to question 2) "This question should be solved by equation $F_b=mg$ or $F_b=\rho gv$. But I was shocked to find that the answers calculated by these two equations were different. Is the buoyant force of objects in outer space different from that on earth?"*

Generally speaking, the intermediate level students appear to have more developed understanding than the novices, they are often to perform effective reasoning by applying the related concepts and principles to obtain the unknown variables. However, their knowledge structures are still not integrated around the central idea and their problem-solving strategies are still relied on applying equations. The following student's responses further confirmed this finding:

Student D: *(Response to question 9) "When the object is stationary, $F_b=mg-Fs$, so options A and B are wrong. When the object is emerging, $F_b \neq mg$, so option C is wrong. The answer is D." (The correct answer is A.)*

Students similar to student C and student D have a good understanding of the connection between buoyant force and the related concepts and principles, so they can often analyze the states and forces of the object, and obtain the variables not directly given in the question through certain transformation methods. As stated in the conceptual framework of buoyant force, these students' knowledge structures need to be more integrated with the central idea to develop some more valid problem-solving strategies.

Expert level: These students are able to solve most of all 12 questions using multiple strategies. For the questions in integrated-link unfamiliar set in particular, they seem to be able to apply it correctly to get the keys to answer the questions on the basis of a deep understanding of the central idea.

Student E: *(Response to question 2) "The origin of buoyant force is that the liquid is affected by gravity, this is A. In outer space, the liquid is not affected by gravity, so the buoyant force is zero."*

Student F: *(Response to question 2) "In this question, the buoyant force is obviously zero. Because the g=0 holds forever in outer space, it doesn't matter whether the equation $F_b=mg$ or $F_b=\rho gv$ is used, the final answer is zero. So, the answer is A." (Response to question 7) "The buoyant force is the net force on the upper and lower surfaces of an object in a liquid, and the object is in equilibrium in this question, so I can get the answer as long as I analyze the forces on the object in the vertical direction. After calculation, the answer should be D."*

As shown in these excerpts, the problem-solving performances of these students are like that of experts. They often started by understanding the essential meaning of buoyant force, and then chose the appropriate approaches. They formed such a basic understanding that buoyant force is an effect force caused by the gravity of the liquid. Through this basic understanding, they can integrate contextual variables, calculation equations, and related concepts and principles to solve the problems successfully.

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The number at each level of the 48 interviewed students included 19 novices, 20 intermediate, and 9 experts. Their average performance on different question sets is shown in Table 4. Considering the small sample sizes, such results are only used as a supplementary reference.

Table 4
The Average Performance of Interviewed Students at Different Levels

Knowledge integration level	Total (%)	Single-link typical (%)	Multilink typical (%)	Integrated-link atypical (%)
Novice	38.16	77.19	40.79	12.63
Intermediate	62.08	88.33	76.25	35.00
Expert	99.07	100.00	100.00	97.78

Putting these interview outcomes together, it is quite evident that the novice level students' knowledge structures were fragmented. Therefore, they can only apply memorized equations to solve the simple questions in familiar contexts. The students at intermediate level had deeper understanding about buoyant force and could solve most multilink familiar questions. Nevertheless, the knowledge structures of these students were still lack of connection with the central idea. As a result, it was difficult for them to solve problems in complex and unfamiliar contexts. The expert level students had established well-integrated knowledge structures so that they could obtain multiple problem-solving strategies by using the central idea. Therefore, they were able to solve most problems effectively.

Discussion

In this study, a conceptual framework of buoyant force was established according to the theory of knowledge integration to guide the modeling and assessment of students' knowledge structures in understanding buoyant force. The results show that this approach can effectively identify and present students' understanding of buoyant force into three different levels of knowledge integration, including novice, intermediate, and expert.

For the novice level students, since they only rely on scattered mnemonic pattern matching to solve related problems, establishing the awareness of concept understanding is the first thing they need to strive to do when learning a related topic. Specifically, they should give up the learning tendency of directly memorizing calculation equations and corresponding variables and try to construct the connection between relevant knowledge elements by looking for certain logical relationships and reasoning pathways. Thus, they can solve problems analytically through meaningful reasoning and explanation, rather than through inefficient and error prone mechanical memory.

For the intermediate level students, they seem to be locally connected among the calculation equations of buoyant force and related concepts & principles, but they still have the tendency of pattern matching in the process of solving problems, even they can successfully choose the proper calculation equations and get the required variables. In other words, they may just be more familiar with calculation equations and remember some corresponding methods to promote the successful application of these equations than novices, but they do not understand the root and essence of the connections between the relevant knowledge elements they have established. Therefore, they need to further understand the central idea to find the nature of the connections between the knowledge elements. Thus, they can effectively solve the problems that need to be solved by applying the central idea rather than simply pattern matching.

For the expert level students, they seem to have developed a deep understanding of the central idea, established effective connections among most key contextual variables and reasoning pathways, and formed a comprehensive knowledge structure. This means that they have found the right way to learn scientific concepts. What they need to do is to explore more logical relationships and reasoning pathways to link more knowledge elements, so as to further expand the formed conceptual framework. As a result, they may solve more complex and difficult related problems.

In this study, the different problem-solving behaviors of the three levels students reveal a process from surface to deep understanding of buoyant force, from memorizing equations to building more networked relationships, and finally to the fully integrated knowledge structure. Through this development process, students show that they

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reduced context dependency, used the central idea more explicitly, and improved accuracy on problem-solving tasks. As is shown by this study, understanding the nature of buoyant force seems to be the key to make this process happen, as it exactly reflects the root causes of various buoyant force related phenomena. Unfortunately, a few Chinese students have understood the essential meaning of buoyant force and formed an integrated knowledge structure, so as to achieve better results in the assessment questions. This shows that the emphasis on understanding the nature of buoyant force and establishing a conceptual framework accordingly may be an effective strategy to help students form an integrated knowledge structure, leading to better problem-solving ability.

Conclusions

Overall, this study shows that the method of constructing the conceptual framework is effective in modeling and analyzing students' understanding in buoyant force learning. The results also show that it is necessary to emphasize the essential meaning of buoyant force to help students develop more integrated knowledge structure and better problem-solving performance. In addition, this study also has some limitations that need to be duly noted. On the one hand, buoyant force is a very complex concept, which is related to many other knowledge elements, so more diversified conceptual frameworks need to be constructed and verified in order to investigate students' understanding of buoyant force more comprehensively. On the other hand, this study was carried out in the Chinese context, whether the constructed conceptual framework of buoyant force, the designed test questions, and the study results are applicable to a wider range need to be further tested.

Declaration of Interest

The authors declare no competing interest.

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Appendix

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The Process of Instruction on Buoyant Force in Chinese lower-secondary schools

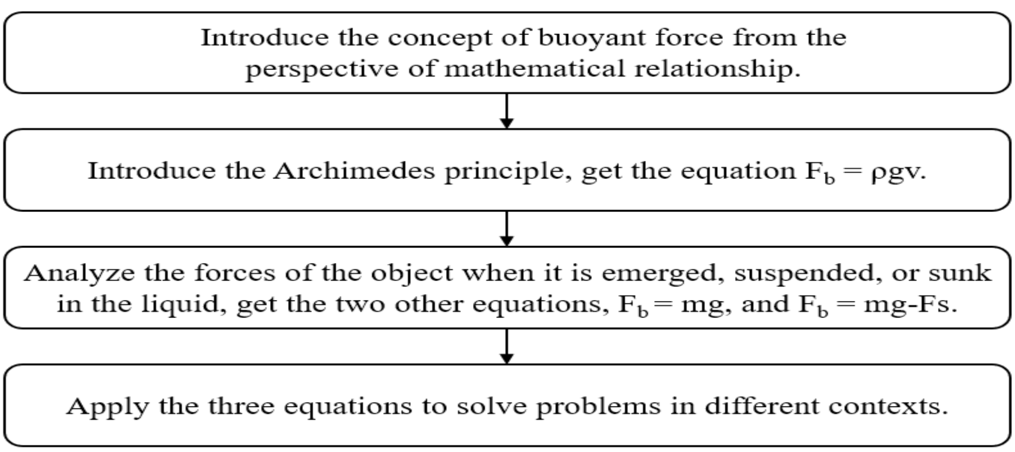
The instruction of buoyant force in Chinese *lower-secondary schools* is delivered in four lectures, each lasting 45 minutes (see Figure 8). In the first lesson, the teacher guides the students to understand the definition of buoyant force and know that every object immersed in a liquid receives an upward buoyant force. It should be noted that the teacher usually pays more attention to introducing the definition of buoyant force from the perspective of mathematical relationship, but only very briefly mentions the nature of buoyant force without any explanation and verification.

In the second lesson, the teacher introduces the Archimedes principle to the students, and guides the students to verify through experiments that the buoyant force is equal to the gravity of the displaced liquid. Then, the students will get the equation $F_b = \rho gv$.

In the third lesson, under the guidance of the teacher, students analyze the forces of the object when it is emerged, suspended, or sunk in the liquid. Then, the students will get the two other equations, $F_b = mg$, and $F_b = mg-Fs$.

In the fourth lesson, the teacher guides students to solve various problems in different contexts to help them get familiar with the relationship between the contextual variables and the equations.

Figure 8
The Process of Instruction on Buoyant Force in Chinese Lower-Secondary Schools



In general, there is no obvious logical clue in the instruction of buoyant force, most teachers usually spend less time on explaining the essential meaning of buoyant force but focus on the training of applying equations to solve problems in different contexts, so that students can be familiar with some fixed problem-solving patterns.

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The Assessment Questions Used in This Study

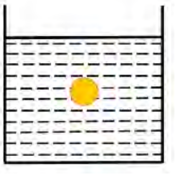
(Tips: if gravity acceleration and water density are involved in the question, g is taken as 10N / kg, and water density is taken as 1.0×10^3 kg/m^3; and in all cases that involving the object is sunk, unless otherwise specified, it is considered that the space between the bottom of the object and the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

1.When an object is placed on the desktop and remains stationary, 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 buoyant force of this object in the water. (B)

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

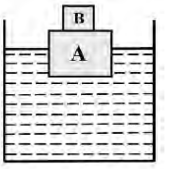
2. As shown in the figure, in outer space, if we put a small ball with volume 3×10^{-6}m^3 and mass 2 g into a cup with water, it would be suspended. What is the buoyant force of this small ball in the water at this time? (A)

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



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

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

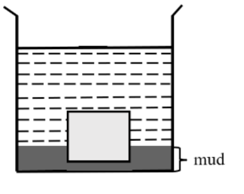


4.As shown in the figure, there is an appropriate amount of water in the container. If we place the wooden block A with a gravity of 5N in the container and press the wooden block B with a gravity of 3N on wooden block A, wooden block A would be emerged on the water with wooden block B. What is the buoyant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

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

5. James puts a small ball with a mass of 0.04kg into a container with water. When the small ball is stationary, the state of it in the water is emerged. Please calculate the buoyant force of this ball in the water. (D)

A.0.1 N B.0.2 N C.0.3 N D.0.4 N



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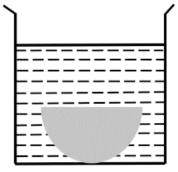
6. As shown in the figure, the object with a volume of 600cm^3 and a gravity of 3N is sunk into the mud at the bottom of the container. It is known that the volume of the object trapped in the mud is 200cm^3, the total embedding force of the mud on it is 7 N, and the force exerted by the water pressures 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 sunk and receive 6N supporting force from the bottom of the container. Please calculate the buoyant force of this object in the water. (A)

A.1 N B.6 N C.7 N D.13 N

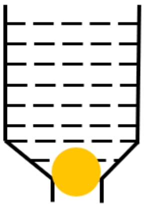
9. As shown in the figure, put the mouth of a lidless and bottomless beverage bottle facing downward, put the table tennis ball (the diameter is slightly larger than the diameter of the bottle mouth) into the bottle and inject water. You can see a small amount of water flowing out of the bottle mouth. 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.

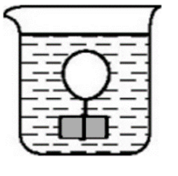
C, In the process of table tennis emerging, the buoyant force it receives is equal to the gravity it receives.

D. In the process of table tennis emerging, the buoyant force 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 buoyant force of this object in the water. (C)

A.5.5 N B.5 N C.4 N D.1 N



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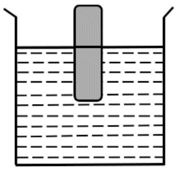
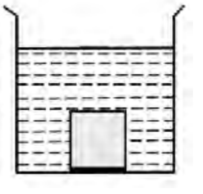
11. As shown in the figure, James puts the cuboid block with a total volume of 180 cm^3 into a container with water. When the block is stationary, the state of it in the water is emerged, and its volume above the water surface is 80cm^3. What is the buoyant force of the cuboid block in the water? (B)

A.0.8 N B.1 N C.1.8 N D.2 N



12. As shown in the figure, 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 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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Yi Zou *(Corresponding author)* PhD, Lecturer, College of Teacher Education, Zhejiang Normal University, Jinhua, China.
E-mail: zouyi88@zjnu.edu.cn

Lizhen Jin MS Student, College of Teacher Education, Zhejiang Normal University, Jinhua, China.
E-mail: jinlizhen99@zjnu.edu.cn

Yanbing Li PhD, Professor, College of Teacher Education, East China Normal University, Shanghai, China.
E-mail: ybli@kcx.ecnu.edu.cn

Tao Hu PhD Student, College of Teacher Education, East China Normal University, Shanghai, China.
E-mail: hutao6277@163.com