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A Study on the Learning Progressions of Understanding the Core Concepts of Kinetic Energy in High School

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Abstract: Learning progressions divide the logical system of a subject into ordered and continuously developing levels that are suitable for the cognitive development level of students, which plays an important role in understanding students' learning process. This paper focuses on the theme of "kinetic energy" in high school physics as the research object. Firstly, the concept map was used to represent the relationship between knowledge, and then five core concepts were selected based on the opinions of high school teachers. Secondly, the test tools were compiled and tested based on the relevant test questions. Finally, the paper analyzed the results based on the Rasch model, clarified students' cognitive development level of "kinetic energy" and constructed the learning progressions of "kinetic energy" based on the logical order of subject knowledge. The research provides theoretical and methodological support for the study of other subjects and learning progressions, and provides a valuable reference for high school teachers to effectively carry out the instruction of "kinetic energy."

Keywords: Core concepts; High school; Kinetic energy; Learning progressions

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1. Introduction

Students' cognitive development goes through a process from low level to high level, and form an understanding of the world through completing tasks of different difficulty levels. With the increasing emphasis on this viewpoint in the field of science education, Smith *et al.* proposed the theory of "Learning Progressions" (LPs) in their report submitted to the National Research Council of the United States by the "Basic Education Stage Science Academic Achievement Evaluation Committee" [1]. LPs refer to a continuous and more skilled way of thinking about a subject, which can develop continuously with the student's learning and exploration of the topic [2]. The learning path students follow when learning a topic is a series of progressive conceptual sequences centered on the core concepts. Therefore, core concepts are the foundation of students' mastery of concepts and the prerequisite for learning progressions.

To cultivate talents with core competency in the new era, the Ministry of Education of China revised the high school curriculum in 2013, condensing the core competencies of physics: physics concept, scientific thinking, scientific exploration, scientific attitude, and responsibility. With the advent of core competencies, Guo and others have conducted a series of learning progressions studies based on core competencies [3-11], which have important practical value in promoting cognitive development, coherent and consistent design of curriculum standards and textbooks, educational evaluation, and teaching decision-making.

Instruction is the activity of teachers to help students learn, so it is necessary to take into account the cognitive development level of students and set the acceptable level of knowledge learning to help students study. Therefore, the premise of effective teaching activities is to clarify students' learning progress based on core concepts. Based on it, this study analyzes the important concepts and constructs the learning progressions based on the topic of "kinetic energy" in high school physics.

2. Research methods

This study took "kinetic energy" in high school physics as the research object, prepared test questions around important concepts, and analyzed students' learning progress. First, according to the Chinese middle school physics curriculum standards and textbooks, XMind software was used to make conceptual maps. The theme of "kinetic energy" was selected as a core concept. Secondly, learning progressions measurement tools were compiled based on EMCS (Energy and Momentum Conceptual Survey) and ECA (Energy Concept Assessment) questions. Thirdly, the second-year students of four high schools in Yanji City, Jilin Province were tested, and the Rasch model was analyzed by ConQuest software [12] to construct the learning progressions of the core concept of "kinetic energy" from the perspective of disciplinary knowledge.

3. Research process and results

3.1. Selection of core concepts

3.1.1. Curriculum standards and textbook analysis

Core concepts reveal the definition of basic knowledge points and their relationships. To select the core concepts under the theme of "kinetic energy," the curriculum standards and textbooks are analyzed first. The curriculum standards are "Compulsory Education Physics Curriculum Standards (2011 Edition)" [13] and "General High School Physics Curriculum Standards (2017 Edition 2020 Edition)" [14]. The 2012 People's Education Press middle school physics textbook and the 2019 People's Education Press high school physics textbook are selected.

3.1.2. Concept map analysis

To present the structure relationship between the concepts of kinetic energy more intuitively, the knowledge structure of the content is analyzed according to the chapter arrangement and content relationship in the textbook, as shown in **Figure 1**.

Based on the above analysis, the core concepts of kinetic energy can be selected, including "work," "gravity potential energy," "force," "gravity," "dynamic energy," "velocity," "resistance," and "total mechanical energy conservation."

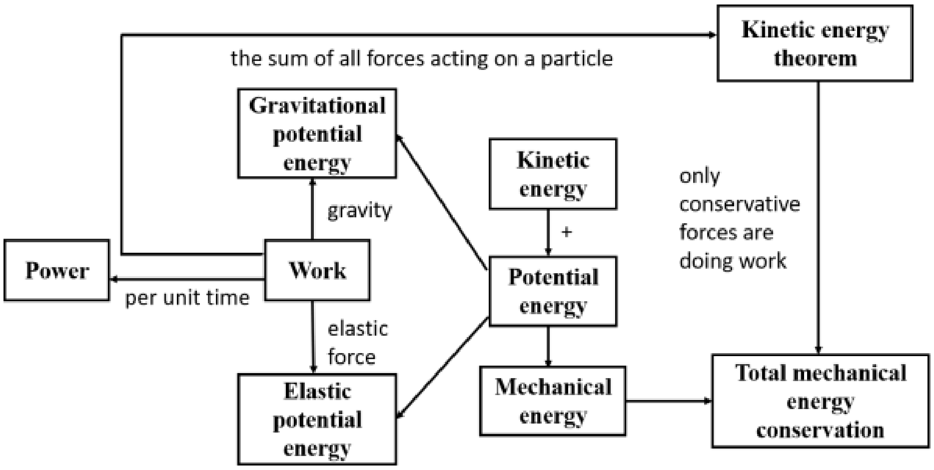

Figure 1. Conceptual diagram of the theme of “kinetic energy”

3.1.3. Analysis of teacher questionnaire survey

The selected core concepts are consistent with the current instruction situation, and it is also necessary to investigate whether teachers approve them. We use the Likert scale to prepare the teacher survey paper, which contains eight core concepts.

Fifty-two papers were distributed to high school physics teachers in the provinces and cities through the online form of Questionnaire Star software, and 52 papers were collected. Using SPSS software to analyze the recovered data, the results of the survey on the recognition of the important concept of “kinetic energy” and its definition are shown in **Table 1**.

Table 1. Teacher recognition of the core concept of “kinetic energy”

Core concepts	Mean	Standard deviation
Work	4.12	0.77
Force	1.70	0.89
Kinetic energy	4.96	0.20
Velocity	3.02	0.52
Total mechanical energy conservation	4.36	0.63
Quality	0.92	0.78
Potential energy	4.26	0.57
Kinetic energy theorem	4.84	0.37

According to the results of the survey, the average scores of five concepts were greater than 4, indicating that the average scores of “force,” “velocity,” and “quality” were 1.70, 3.02, and 0.92, respectively. Finally, five important concepts of “kinetic energy” are identified based on the results of the first-line teachers, namely “work,” “kinetic energy,” “potential energy,” “kinetic energy theorem,” and “total mechanical energy conservation.”

3.2. Test objects and tools

3.2.1. Test objects

In this study, students from four high schools in Yanji City, Jilin Province, were tested in seven high school science classes to ensure that students of different cognitive levels could be investigated. 286 questionnaires were distributed and collected on the spot. The recovery rate of 286 questionnaires was 100%, of which there were 269 effective questionnaires with an effective rate of 94%.

3.2.2. Test tools

The selection of testing tools requires scientific and authoritative characteristics. Many scholars in China used the American Mechanical Concept Test (FCI) to conduct educational research, and more and more test questions were used in the later stage. For example, Yuying Guo has tested students' comprehension levels through electromagnetism-related test questions, and many scholars use energy-related test questions to construct advanced learning levels. These questions are from the American Association of Physics Teachers (AAPT) website, which is dedicated to helping teachers improve their teaching by providing physical education research resources.

The ECA (Energy Concept Assessment) and EMCS (Energy and Momentum Concrete Survey) questions were downloaded through the American Association of Physics Teachers website.

The results were analyzed by the software ConQuest, including reliability, difficulty level, and students' ability, and the distribution of difficulty level and subject's ability. Based on the results of the data analysis, this paper provides a visual basis for constructing the learning progress. ConQuest has 269 samples with a mean value of 13.19, standard deviation of 4.30, variance of 18.51, mean standard error of 0.26, and reliability of 0.79, which indicates that the reliability of this set of questions is relatively good. Analysis of the Rasch model found that the Rasch standard error did not exceed ± 0.75, and the Infit MNSQ index of each question was between 0.7 and 1.3, indicating that the fit of each question was acceptable.

In classical test theory, the difficulty value is the degree of difficulty, the traditional difficulty value can reflect the difficulty of the topic, the larger the value, the less difficult it is. The difficulty range of the test questions is -2.62 to 1.90, and the span is 4.52, indicating that the difficulty distribution of the questions is more uniform and moderate, and can distinguish students with different ability levels.

The Rasch model can scale students' abilities and difficulty in a single scale, the White chart, to visually see the student's ability to do a certain problem. The value at the left end of the White chart represents the level of students and the difficulty value of the problem, and the "×" in the middle represents the student, and test takers' levels rise sequentially from bottom to top. The right end represents all the questions numbered in the order of the questions, and the difficulty of the questions increases sequentially from the bottom up, as shown in **Figure 2**. The distance between projects represents the difference in difficulty between projects, and the closer the project is to the upper end of the horizontal axis, the less difficult it is to the lower end.

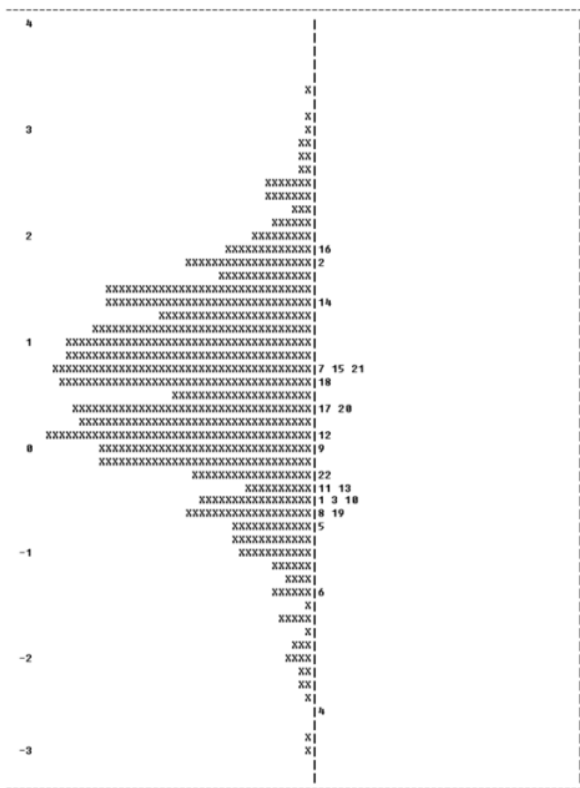

Figure 2. White diagram

3.3. Learning progressions construction of core concepts on the topic of "kinetic energy"

The elements of constructing learning progressions include learning objectives, advanced variables, intermediate level, learning performance, and evaluation. This study uses knowledge content as the advanced variable and constructs the advanced level based on the cognitive development order of students. Based on the analysis of curriculum standards and textbooks, as well as the survey results of frontline teachers' recognition of important concepts, five important concepts and related knowledge were ultimately selected. By analyzing and surveying the questionnaire on students' mastery of important concepts, the difficulty level of the questions, the specific fitting situation of the questions, and the distribution of project and participant abilities are obtained, providing an effective basis for constructing corresponding learning advancement.

3.3.1. Learning progressions construction of core concepts on the topic of "work"

The knowledge points examined in this section of work can be divided into three dimensions, including the concept of work, understanding the characteristics of work, and the application of work. The number of knowledge points examined in each dimension varies.

Advancement is a gradual process from shallow to deep, requiring multiple intermediate levels to lay the foundation for achieving the ultimate learning goal. The sequential division of advanced levels is crucial, and the starting point, intermediate level, and endpoint of advancement can be determined based on the difficulty of the questions and the student's ability level. Gong is the foundation of learning kinetic energy, and it is also the first concept that students learn. Therefore, Gong can be divided into advanced starting points; determine the formula for the work done by a certain force as an advanced intermediate level; the concept of total skill belongs to a high-level advancement.

Based on the above analysis, the specific expression of the learning advancement level of “work” is shown in **Table 2** below.

Table 2. Learning progressions for “work”

Level	Learning progressions
Level 1	Knowing the formula $W=Fl$ for work, and the fact that when the direction of force F is perpendicular to the direction of displacement l, the force does not perform any work, one can accurately judge when work is being done and when it is not.
Level 2	Furthermore, recognizing that work can have positive and negative values and is a scalar quantity, one can determine the nature of the work being done, whether it is positive or negative.
Level 3	Additionally, understanding that the work done by a force on an object is equal to the product of the magnitude of the force, the magnitude of the displacement, and the cosine of the angle between the force and the displacement, represented by $W=Flcos\ \alpha$, enables us to use this formula for calculations.
Level 4	Lastly, knowing that the total work done by the resultant force on an object is equivalent to the work done by the resultant force itself or the algebraic sum of the work done by each individual force acting on the object, we can employ vector operations to determine the resultant force.

3.3.2. Learning progressions for “potential energy”

The potential energy section focuses on examining the characteristics of gravitational potential energy and elastic potential energy, as well as their relationship with work. Potential energy includes gravitational potential energy and elastic potential energy. In junior high school, students have qualitatively learned about gravitational potential energy and elastic potential energy, and know that the factors that affect gravitational potential energy are the mass and height of an object’s position, and the factors that affect elastic potential energy are elastic deformation variables. Using the concept of potential energy as an advanced starting point; determine the analysis of the change in potential energy as an advanced intermediate level; determine the functional relationship as a higher-level advancement.

Based on the above analysis, the specific expression of the learning advancement level of “potential energy” is shown in **Table 3**.

Table 3. Learning progressions for “potential energy”

Level	Learning progressions
Level 1	Potential energy includes gravitational potential energy and elastic potential energy, gravitational potential energy is shared by the “system” composed of the Earth and objects, determined by the relative positions of the Earth and objects on the ground, while elastic potential energy is determined by the relative positions of various parts of the object undergoing elastic deformation.
Level 2	The formula for gravitational work is $W=mgh$, where “h” refers to the height difference between the initial and final positions and is independent of the path of motion; Knowing the gravitational potential energy formula $E_p=mgh$, where h refers to the height of the position, one should be able to distinguish the meaning of h in the two formulas and perform simple calculations.
Level 3	Knowing that gravitational potential energy has relativity, choosing different reference planes results in different values of gravitational potential energy, but the change in gravitational potential energy ΔE_p remains unchanged. Knowing that elastic potential energy is related to the length and stiffness coefficient of the spring being stretched or compressed. One can feel the connection between functions.
Level 4	Knowing that work is a process quantity and potential energy is a state quantity. Understanding work is a measure of energy conversion, where the value of work done by the corresponding force is equal to the change in potential energy at the initial and final positions, i.e. $W=E_{p1}-E_{p2}$. Gravity (elasticity) does positive work, and gravitational potential energy (elastic potential energy) decreases; gravity (elasticity) does negative work, and gravitational potential energy (elastic potential energy) increases. To be able to apply functional relationships to explain phenomena in daily life.

3.3.3. Learning progressions for "kinetic energy"

The advanced variables of kinetic energy content include the characteristics and applications of kinetic energy. Students have already been exposed to kinetic energy in junior high school and know that the kinetic energy of an object is related to its mass and velocity. The greater the mass and velocity, the greater the kinetic energy. In high school, one should delve deeper into the formulas of kinetic energy and the changes in kinetic energy. Using the simple calculation of kinetic energy formula as an advanced starting point for this section; determine the relationship between kinetic energy and velocity as an advanced intermediate level; the application of kinetic energy belongs to a high-level advancement.

Based on the above analysis, the specific expression of the learning advancement level of "kinetic energy" is shown in **Table 4**.

Table 4. Learning progressions for "kinetic energy"

Level	Learning progressions
Level 1	Kinetic energy is the energy possessed by an object due to its motion. Its size is defined as half of the product of the mass of the object and the square of its velocity, that is, the unit is *J*. Able to perform simple calculations based on formulas.
Level 2	Velocity is a vector, but kinetic energy is a scalar and always greater than or equal to 0. Changing the direction of velocity will not cause a change in kinetic energy.
Level 3	Understanding that kinetic energy E_k is the state variable of an object's motion, and the change in kinetic energy ($\Delta E_k = E_{k2} - E_{k1}$) is a process variable related to physical processes, such as the change in gravitational potential energy.
Level 4	Using the isolation method and the holistic method to analyze problems. When the research object is two or more objects, the holistic method can be used to analyze several objects as a whole, and it is clear that objects have kinetic energy as long as they move, and the whole has kinetic energy.

3.3.4. Learning progressions for "kinetic energy theorem"

The content of the kinetic energy theorem is a synthesis of the previous learning, mainly examining the application of the kinetic energy theorem, such as in the case of constant force and variable force work, and linear and curved motion. The kinetic energy theorem is the relationship between work and the change in kinetic energy, that is, the work done by a force on an object in a process is equal to the change in kinetic energy of the object in that process. Determine the basic concept of the kinetic energy theorem as the starting point for advancement; using the conditions and characteristics of the kinetic energy theorem as an intermediate-level advancement; based on the White diagram, it can be determined that the work done by the combined force can be considered as a higher-level advancement.

Based on the above analysis, the specific expression of the advanced level of learning about the "kinetic energy theorem" is shown in **Table 5**.

Table 5. Learning progressions for "kinetic energy theorem"

Level	Learning progressions
Level 1	The kinetic energy theorem states that the work done by force on an object during a process is equal to the change in kinetic energy of the object during that process. Able to perform simple calculations of kinetic energy and work based on formulas.
Level 2	The kinetic energy theorem is not only applicable to constant force work and linear motion but also to variable force work and curved motion. Understand the wide applicability of the kinetic energy theorem and be able to apply it in a simple way.

Table 5 (Continued)

Level	Learning progressions
Level 3	Understanding the process of applying the kinetic energy theorem and determining the initial and final states, as well as determining the positive and negative work, is crucial and can be analyzed clearly.
Level 4	Knowing that if an object is subjected to the combined action of several forces, the work W in the kinetic energy theorem is the total work, which is the work done by the resultant force on the object (or understood as the sum of the work done by each component force on the object). The ability to apply the kinetic energy theorem to analyze slightly more complex phenomena in daily life and solve related problems is essential.
Level 5	Further understanding the relationship between work and kinetic energy, that is, when the combined force does positive work on an object, the kinetic energy of the object increases, and when it does negative work, the kinetic energy of the object decreases, and able to apply knowledge to practical life.

3.3.5. Learning progressions for "total mechanical energy conservation"

The content of conservation of mechanical energy mainly examines the conditions for the conversion and conservation of energy. The advanced starting point, intermediate level, and endpoint determined based on the difficulty of the questions and students' ability values are as follows: Students have learned mechanical energy in junior high school and know that gravitational potential energy, elastic potential energy, and kinetic energy are all forms of energy in mechanical motion, collectively referred to as mechanical energy; knowing that by doing work, mechanical energy can be transformed from one form to another (knowledge learned in junior high school is not reflected in advanced studies). In high school, it is further studied functional relationships and understood that in an object system where only gravity or elasticity work, kinetic energy and potential energy can be converted into each other, while the total mechanical energy remains constant. Using the law of conservation of mechanical energy as a starting point for advancement; using system selection as an intermediate level for advancement; determining the non-conservation of mechanical energy as the highest level of advancement. Based on the above analysis, the specific expression of the advanced level of learning about the "kinetic energy theorem" is shown in **Table 6**.

Table 6. Learning progressions for "total mechanical energy conservation"

Level	Learning progressions
Level 1	Knowing that gravitational potential energy, elastic potential energy, and kinetic energy are collectively referred to as mechanical energy. Knowing the law of conservation of mechanical energy, which states that in an object system where only gravity or elasticity works, kinetic energy and potential energy can be converted into each other, while the total mechanical energy remains constant.
Level 2	Clearly understanding the importance of the system and knowing that when determining whether mechanical energy is conserved, the system must be selected first.
Level 3	Understanding several situations of conservation of mechanical energy and being able to apply them, that is, an object is only affected by gravity, and the system composed of the object and the Earth is subject to conservation of mechanical energy; only gravity does work, other forces do not do work, and the mechanical energy of the system composed of objects and the Earth is conserved; only the elastic force of the spring does work, other forces do not do work, and the system composed of the object and the spring conserve mechanical energy; only gravity and spring elasticity do work, while other forces do not. The system composed of objects, springs, and the Earth conserves mechanical energy.
Level 4	Knowing that mechanical energy is not conserved when there is a systematic external or non-conservative internal force doing work, and the sum is not zero.

4. Conclusion

Through a series of investigations, this study finally obtained learning progressions for core concepts under the theme of “kinetic energy.” However, its structural order is slightly different from that of textbooks and curriculum standards in China.

Firstly, there are no specific requirements for the knowledge point of “system” in the curriculum standard, but the “system” often appears in many parts, such as gravitational potential energy. While “system” is easy to understand, it is not clear to most students.

Secondly, the order of some core concepts in curriculum standards is slightly different from that of textbooks. For example, the textbook arranges kinetic energy expressions through velocity association and derivation in conjunction with Newton’s second law. However, it causes students to develop many misconceptions about kinetic energy. Therefore, the relationship between velocity and kinetic energy should be added to help students fully understand kinetic energy.

Through the construction of the learning progressions of the important concepts of “kinetic energy” in high school physics, the thinking level of students learning the core concepts of “kinetic energy” is deeply understood. Teachers should realize that teachers’ instruction activities should be arranged in line with students’ thinking levels. Teachers can learn from the study to improve the teaching effect of the physics “kinetic energy,” and researchers in related fields can also refer to the study method to study other subjects or other topics.

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Disclosure statement

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