Teaching Design and Implementation Based on the Problem-Chain Teaching Model: Taking "Sum of the First *n* Terms of an Arithmetic Sequence" as an Example

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Abstract: Problem-based teaching has always been an important form in middle school mathematics teaching. Taking "the sum of the first *n* terms of an arithmetic sequence" as an example, this paper combines the problem-chain teaching model to bring students into a scenario and put forward phased problems step by step. It guides students to gradually connect the inquiry tasks in the problems with the learned knowledge, helps them understand the essence of "pairing thought", "term number calculation" and "reverse summation method", and master the formula for the sum of the first *n* terms of an arithmetic sequence. At the same time, it develops core competencies such as mathematical abstraction, logical reasoning and mathematical modeling, providing a replicable practical paradigm for high school mathematics concept teaching.

Keywords: Problem-chain Teaching Model; High School Mathematics; Sum of the First *n* Terms of an Arithmetic Sequence; Core Competencies

1. Introduction

Competency-oriented mathematics teaching emphasizes "letting students experience the formation and application process of mathematical knowledge and master knowledge from the process". As a bridge connecting "knowledge transmission" and "competency cultivation", problem chains can guide students to think deeply through systematic problem sequences [1]. Compared with the "fragmented questioning" of traditional educational models, problem chains are characterized by "logical coherence and hierarchical progression", transforming textbook content into explorable tasks. Students will consciously extend reasonable thinking goals and gradually construct a complete knowledge system during the teaching process, thereby improving the quality of their thinking.

"The sum of the first n terms of an arithmetic sequence" is the core content of the sequence chapter. It connects the definition and general term formula of arithmetic sequences, and lays a foundation for the subsequent sum of geometric sequences, practical applications of sequences and derivative-based to solve the extremum of sequence. The important mathematical methods contained in its formula derivation process, such as "Gauss's pairing thought" and "reverse summation method", are high-quality carriers for cultivating students' logical reasoning and mathematical abstraction competencies [2]. However, there are three major pain points in traditional teaching: first, "emphasizing formula memory over process inquiry". Under the operation of multiple disciplines, students rely on memorization to reduce the burden and ignore the mathematical ideas contained in the methods; second, "lack of systematicity in problem design". Most questions focus on a single knowledge point, failing to form a thinking closed loop. Students' thinking on key knowledge cannot be elevated, and they cannot solve higher-level problems; third, "disconnection between scenarios and knowledge". In the introduction process, students cannot anticipate the knowledge of this lesson, making it difficult to stimulate their inquiry interest and application awareness[3].

Based on this, this paper takes "the sum of the first n terms of an arithmetic sequence" as the teaching content, draws on the design framework of "scenario problem leadership, core problem decomposition, and sub-problem implementation" [4], organically integrates the ancient cultural relic restoration scenario with mathematical culture, and guides students to experience a complete cognitive process through gradient problem chains, realizing the dual goals of knowledge construction and competency cultivation.

2. Overview of Problem-Chain Related Theories

2.1 Problem-Chain Teaching Model

The problem-chain teaching model takes problems as the core. It guides students to gradually deepen their learning in the process of solving problems through designing a series of interrelated and progressive problems, so as to achieve a comprehensive understanding and mastery of knowledge. In this model, the teacher's role transforms from a traditional knowledge disseminator to a guide, organizer and manager of students' learning. Teachers need to carefully design problem chains according to teaching goals, teaching content and students' cognitive levels, which are interlocking, so that students can explore problems with tasks and enhance their understanding of knowledge. The problem-chain teaching model emphasizes the dominant position of students, focuses on stimulating students' learning interest and initiative, and guides students to actively participate in learning activities through designing interesting problems and scenarios. At the same time, this model also focuses on cultivating students' thinking abilities. By designing challenging problems, it guides students to think deeply and explore, and cultivates their logical thinking abilities, as well as abilities to analyze and solve problems. In addition, the problem-chain teaching model has strong practicality and applicability. Through designing practical problems and cases, it guides students to apply the learned knowledge to practical scenarios and solve practical problems, thereby improving their practical and application abilities

2.2 Overview of Types of Problem-Chain Design

In the field of education research at home and abroad, there are various types of problem chains. Combined with textbook content and students' characteristics, this paper summarizes the types of problem chains applicable in mathematics classrooms. Each type has its own unique characteristics and is suitable for different teaching scenarios. Specifically, there are the following four types:

2.2.1 Guided problem chains

Guided problem chains start with questions raised by teachers to quickly clarify the research direction [5]. Their primary goal is to attract students' attention and stimulate their curiosity in the first place, allowing students to discover and summarize laws in the process of exploring problems, and experience the formation of concepts and principles. Secondly, they lay the foundation for subsequent learning content, helping students establish connections between new and old knowledge through methods such as analogy, deduction and induction. This type of problem chain is often used in the introduction of new courses, which can quickly lead students to find learning directions and goals, understand the teaching content of the course, and smoothly complete the transition of the course.

2.2.2 Diagnostic problem chains

Diagnostic problem chains focus on the key points, difficulties, doubts and error-prone points of the teaching content, and carefully design targeted questions [3]. They aim to mobilize students' reflective abilities, guide them to think deeply about the doubts in the problems, and cultivate their ability to draw inferences from one instance. Starting from error-prone points, they enhance students' sensitivity to mathematical concepts, avoid missing key thinking points in the problem-solving process due to insufficient understanding of concepts, help students consolidate the foundation, and improve their accurate grasp of knowledge.

2.2.3 Summarative problem chains

Summarative problem chains are suitable for the summary and review stages of courses, and comprehensively summarize the entire course system [6]. They can help students review the teaching content, consolidate knowledge points, strengthen the application of mathematical ideas, and exercise mathematical thinking abilities. At the same time, they facilitate teachers to guide students to connect the knowledge of this chapter into a network and construct a knowledge system. Students conduct induction and summary according to the problem chains, form their own knowledge structure and network, achieve a clear understanding of the course or chapter, and improve their self-inspection and reflection abilities.

2.2.4 Progressive problem chains

The difficulty of problems in progressive problem chains gradually increases, showing a gradient from easy to difficult. Moreover, the problems are closely related to each other, providing students with a process of gradual adaptation. They conform to students' cognitive laws and guide students to explore deeper knowledge [7]. They have a wide range of applicability. They are not only suitable for the application scenarios of the aforementioned three types of problem chains, but also can be used for after-class assignments in the form of hierarchical assignments, meeting the needs of students with different academic levels, helping students make steady progress on the original basis, and realizing personalized learning and development

3. Teaching Analysis

3.1 Textbook and Curriculum Standard Analysis

This section "the sum of the first n terms of an arithmetic sequence" is selected from Section 4.2 of the Selective Compulsory Volume 2 of High School Mathematics (People's Education Press Edition A). It is located between "the concept of arithmetic sequence" and "geometric sequence", and plays a pivotal role in connecting the preceding and the following knowledge. From the perspective of textbook arrangement logic, the previous content "the concept and general term formula of arithmetic sequence" provides the "basic quantities (a_1, d, a_n)" for the summation formula, and students already have a cognitive foundation. This section also lays a foundation for the subsequent "sum of the first n terms of a geometric sequence", which can be carried out by analogy with the idea of arithmetic sequence summation, allowing students to form a complete method system of "sequence summation".

《The General High School Mathematics Curriculum Standards (2017 Edition, Revised in 2020)》 clearly requires this section: "Explore and master the formula for the sum of the first n terms of an arithmetic sequence, understand the internal connection between the 'general term formula' and the 'sum of the first n terms formula' of an arithmetic sequence, and be able to use the formula to solve simple practical problems" [8]. From the perspective of curriculum standards, "explore" points to process requirements, emphasizing that students need to experience the thinking process of deriving the "summation formula"; "master" points to result requirements, requiring students to flexibly apply the formula for summation calculation; "understand the connection" points to transfer requirements, needing to help students establish a logical connection between the "general term formula" and the "summation formula" in their minds; "solve practical problems" points to application requirements, requiring students to connect the content of this section and solve problems independently when encountering similar scenarios.

The textbook introduces the "Gauss summation" case, and gradually transitions to the summation of general arithmetic sequences, reflecting the mathematical thought of "from special to general"; at the same time, it infiltrates methods such as "reverse summation method" and "combination of number and shape (analogy with trapezoidal area)", providing carriers for the cultivation of core competencies. Teaching should closely follow the textbook logic, strengthen "process" and "applicability", and avoid simplifying formula derivation into "conclusion memory".

3.2 Student Situation Analysis

3.2.1 Existing foundations

(1) Knowledge foundation: Students have mastered the definition of arithmetic sequences (from the second term, the difference between each term and the previous term is a constant d), the general term formula ($a_n = a_1 + (n-1)d$), and can judge whether a sequence is an arithmetic sequence; they are proficient in integer addition operations and understand the application of "commutative law of addition" and "associative law of addition";

(2) Thinking foundation: They have the inductive thinking of "from special to general" (such as inducing the general term formula through specific sequences), and have preliminary experience in "Gauss's pairing summation ($1 + 2 + \dots + 100$)"; they can complete simple inquiry tasks through group cooperation, such as discussing the regular characteristics of sequences;

(3) Ability foundation: They have basic mathematical reading ability (can extract known conditions from problems) and computing ability (can perform simplification and calculation of integral expressions and fractional expressions), but their awareness of transforming practical scenarios into mathematical models is weak.

3.2.2 Cognitive difficulties

(1) Difficulty in understanding the essence of methods: Students are prone to mechanically imitate the steps of the "reverse summation method", but it is difficult to grasp its core—transforming the "summation of arithmetic sequences" into the "summation of constant sequences with (sum of first and last terms × number of terms)". Students know "how to reverse the order", but have insufficient understanding of the logic of "why to reverse the order" and "how to transform after reversing the order";

(2) Difficulty in distinguishing formula applications: When facing different known conditions given by problems (such as "known first term, last term, number of terms" vs "known first term, common difference, number of terms"), they are prone to confusing formula selection; when calculating, they are prone to ignoring the accurate judgment of the "number of terms n" (such as the number of terms in the sequence $2 + 3 + ... + 92$ is 91, not 90 or 92);

(3) Difficulty in transforming practical modeling: From real scenarios such as "ancient cultural relic gem arrangement" and "step decorative lights", it is difficult to quickly abstract the "first term (quantity of the first row), common difference (quantity difference of each row), number of terms (total number of rows)", lacking a transformation bridge for mathematizing practical problems.

3.3 Teaching Objectives

(1) Through the progressive inquiry process of "Gauss's pairing summation—discovering method limitations—reverse summation inquiry—general formula derivation", students can understand the derivation logic of the two formulas for the sum of the first n terms of an arithmetic sequence ($S_n = \frac{n(a_1+a_n)}{2}$, $S_n = na_1 + \frac{n(n+1)}{2}d$), and distinguish the known conditions of "known first and last terms and number of terms" or "known first term, common difference and number of terms" to select the correct summation formula. They will develop core competencies of mathematical abstraction (abstracting general formulas from specific sequence summation) and logical reasoning (recursive argumentation of reverse summation), experience mathematical ideas of "from special to general" and "transformation and reduction", and reach Level 2 of high school mathematics academic quality.

(2) Through the process of modeling and solving practical problems in ancient relic restoration—from calculating the total number of gems in a single building to solving for the total gem quantity across multiple buildings—students will be able to select the corresponding summation formula based on the known conditions of an arithmetic sequence (first term(a_1), last term (a_n), common difference d, number of terms n).

Adopting the task-driven, scenario-based, problem-chain teaching model [9] to organize unit teaching tasks, students will complete the full problem-solving process: identifying known quantities → calculating the number of terms → substituting into formulas → verifying results. This approach enables students to solve simple practical application problems involving sequences, develop the core competencies of mathematical operation (accurately performing the sum of the first n terms of a sequence) and mathematical modeling (transforming practical problems into arithmetic sequence models), enhance their ability to analyze and solve problems, and ultimately meet Level 2 of the High School Mathematics Academic Standards.

(3) By experiencing the study and group sharing process of the historical development of arithmetic sequence summation such as Gauss's clever calculation story, Pythagorean triangular numbers, and ancient Chinese stacking techniques [10], students can understand the historical development process of arithmetic sequence summation, compare and explore the essential connections between multiple methods such as "reverse summation method", "trapezoidal area analogy method" and "stacking technique", cultivate confidence in mathematical culture, form rigorous and realistic mathematical thinking habits (such as verifying the accuracy of term number calculation and checking the rationality of formula application), enhance the learning cognition of "mathematics comes from life and is used in life", and reach Level 1 to Level 2 of high school mathematics academic quality.

4. Teaching Practice Based on the Problem-Chain Teaching Model

Session 1: Consolidate Old Knowledge and Transition to New Courses

Scenario: Liang Chen is an ancient cultural relic restorer. Now he needs to restore the roof of a dilapidated ancient building. Its roof structure is shown in Figure 1 below, which is called a curved eave gable roof. In addition to repairing the damaged tiles and some structures of the roof, the cultural relic restorer Liang Chen also needs to some inlay gorgeous gems on the side of the roof of the building to restore the magnificent and dignified beauty of the ancient building displayed in history. The location of the inlaid gems is shown in Figure 2 below. One gem is needed at the highest point of the inlay, two gems are needed in the next row, three gems are needed in the third row and so on until the last layer.

Figure 1. Building with Curved Eave Gable Roof

Figure 2. Schematic Diagram of Gem Inlay Position (Red Circle Position)

Question 1: What kind of law does the number of gems inlaid in rows on the side of the roof follow?

Teacher: Follow-up question: Have we learned a similar mathematical model before for this arrangement law? Which type of mathematical model does it belong to?

Student: By observing that the number of gems inlaid on the side of the roof satisfies the law that each layer has one more gem than the previous layer, they associate it with the definition of an arithmetic sequence: a sequence where the difference between each term and its previous term is equal to the same constant starting from the second term.

Answer: The law of these gems satisfies an arithmetic sequence.

Teacher: Follow-up question: Suppose 100 layers of gems are now built, how many gems are there in the first layer? How many gems are there in the last layer? What is the difference in the number of gems between the upper and lower layers?

Student: Answer: There is 1 gem in the first layer, 100 gems in the last layer, and the difference in the number of gems between the upper and lower layers is 1.

Teacher: Follow-up question: You just answered that the arrangement law of these gems satisfies an arithmetic sequence. Think about what the first term a_1, last term a_n, and common difference d of this arithmetic sequence are respectively?

Student: Answer: The first term a_1 is 1, a_n is 100, and d is 1.

Teacher: Follow-up question: How many gems are there in the nth row? Please calculate it using scratch paper.

Student: Calculate on scratch paper that the number of gems in each row is one more than the previous row, and obtain the general term formula for the number of gems: $a_n = 1 + (n-1) \times 1 = n$.

Answer: There are $a_n = 1 + (n-1) \times 1 = n$ gems in the nth row.

Teacher: Summarize the problem: This project conforms to the arithmetic sequence we learned before. There is 1 gem in the first row, 2 gems in the second row, and so on, 100 gems in the last row, and each row has 1 more gem than the previous row.

Design Intention: Based on textbook knowledge and integrating the concepts of the new curriculum standard, this section starts with a simple question to create a scenario. By continuously putting forward phased questions and advancing in a step-by-step manner [11], it encourages students to think hands-on and review the key knowledge points learned in the previous lesson. This not only consolidates students' mastery of knowledge but also engages them in practical calculations to activate their thinking. It enhances students' core competencies in logical reasoning and mathematical operation, facilitates better absorption of knowledge, stimulates their learning interest [12], and thus smoothly introduces the new topic.

Session 2: Deepen the Scenario and Introduce New Knowledge

Scenario: Based on the above scenario, the cultural relic restorer Liang Chen is going to collect enough gems to build.

Question 2: Please help the cultural relic restorer figure out how many such gems need to be collected and made in total?

Teacher: Follow-up question: How can students quickly calculate the total number of gems needed? Please think and calculate in groups.

Student: In the process of thinking, some students count the total number of gems in 100 rows by counting, some students calculate $1+2+......+100$ using scratch paper, and others discuss thinking in the direction of arithmetic sequence knowledge.

Teacher: Observe the group discussion of students and begin to tell Gauss's story: When Gauss was a child, facing the problem of calculating $1+2+......+100$, he used a special calculation method. He added 1 and 100, 2 and 99, 3 and 98, and so on, and could form 50 pairs of 101 in total. We call this idea Gauss's "pairing thought". Next, please calculate the result using this method.

Student: Students begin to calculate $1+2+......+100$ as 5050 using the "pairing thought" on scratch paper.

Scenario: While restoring this ancient building, Liang Chen's colleagues, the cultural relic restorer, discovered an ancient building complex not far away. Many buildings with curved eave gable roofs also need to be restored. According to the surveyed data, the number of gems needed for one of the ancient buildings is $2+3+4+...+90+91+92$ (sum of the number of gems needed in each row), and the number of gems needed for the restoration of other ancient buildings varies.

Question 3: Please try to solve this problem using the Gauss's pairing thought just learned

Teacher: Follow- up question: Observe whether each term in this formula still conforms to our arithmetic sequence?

Student: With the thinking from the previous question, students quickly answer affirmatively.

Teacher-student activity:

Teacher: "However, when we solve the problem, we find that the formula in Question 2 has 100 terms, which can be paired into 50 pairs through the pairing thought, and the number of gems can be quickly solved. How many terms are there in the formula in Question 3? How should we solve it?" And guide students to summarize "number of terms n = last term - first term + 1".

Students: 91 terms using the formula, and find that 45 pairs of 94 can be formed through the pairing thought, with one extra term in the middle, making it difficult to calculate the total number.

Teacher: Follow-up question: Then, facing the large number of ancient buildings in the complex, can you help the cultural relic restorer come up with a formula that can directly calculate the number of gems needed for the side of the roof of different buildings? That is, we can understand that we need to solve the following formula: $1+2+3+...+(n-1)+n\ =?$

Design Intention: Starting from intuition, in line with students' cognitive laws, this session allows students to achieve a preliminary perceptual understanding of arithmetic sequence summation based on the learned Gauss's "pairing thought", and then shows the limitations of the "pairing thought" through effective questions, laying the foundation for the next step of constructing the concept of the arithmetic sequence summation formula.

Session 3: Cooperative Inquiry and Master New Knowledge.

Teacher: By consulting ancient documents, the cultural relic restorer Liang Chen found that when the ancient Greek Pythagorean school studied the concept of numbers, they recorded the concept of "triangular numbers". Triangular numbers refer to the sum of consecutive integers starting from 1, and the number of points is calculated in a triangular arrangement. As shown in Figure 3 below, the method for solving triangular numbers is to move the last row of the original triangular number with n rows to the first row and combine it with the original first row, that is, there are $n+1$ points in the first row after moving; then move the last row of the original triangular number with $n-1$ rows to the second row and combine it with the original second row, that is, there are $(n-1)+2=n+1$ points in the second row after moving... and so on, we can get n rows with $n+1$ points each. Then triangular number = $\frac{n(n+1)}{2}$.

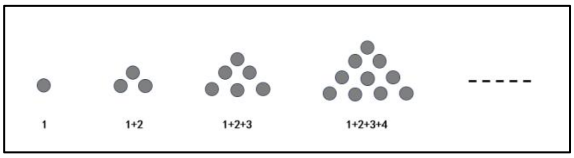

Figure 3. Schematic Diagram of Triangular Number Arrangement

Question 4: Please use the method for solving triangular numbers just learned to find the result of $2+3+4+...+90+91+92$, which was surveyed earlier.

Student: According to the method similar to solving triangular numbers, we can get $2+3+4+...+90+91+92=\frac{91\times94}{2}=4277$.

Teacher: This method is what we call "reverse summation". If in a sequence, the sum of two terms equidistant from the first and last terms is equal to the sum of the first and last terms, we can add the two sum formulas written in the forward order and the reverse order to get the sum of a constant sequence. This summation method is called the reverse summation method. The essence of the reverse summation method lies in transforming the summation of different sequences into the summation of constant sequences.

Question 5: Please think about whether the reverse summation method is applicable to the summation of all sequences, and can we derive the summation formula for the formula $1+2+3+...+(n-1)+n\ =?$

Student: Using the reverse summation method, add the formula $1+2+3+...+(n-1)+n$ and the formula $n+(n-1)+(n-2)+...+3+2+1$, and can derive the summation formula of the arithmetic sequence as $s=\frac{n\times(a_1+a_n)}{2}$.

Teacher: That's right. This is one of the summation formulas for the arithmetic sequence we have. In this lesson, starting from Gauss's pairing thought, we solve the formula for the sum of the first n terms of an arithmetic sequence and find its limitations. At the same time, we introduce triangular numbers, then explore the reverse summation thought contained in them and integrate it into the derivation of the formula for the sum of the first n terms of an arithmetic sequence, and finally obtain the summation formula of the arithmetic sequence $S_n=\frac{n\times(a_1+a_n)}{2}$ Are there other expressions for the formula for the sum of the first n terms of an arithmetic sequence? This question is left for students to think about after class, and we will study it in the next lesson. Next, please complete the following two examples to help the cultural relic restorer Liang Chen calculate and solve the restoration work of the last few buildings.

Design Intention: From special to general, through teacher guidance, this session abstracts the formula for the sum of the first n terms of an arithmetic sequence together with students, gives play to the leading role of teachers and the main role of students, cultivates students' abstract generalization ability, and overcomes teaching difficulties. It directly hits the core of concept teaching, highlights the process of concept formation, allows students to know the reason behind it, and becomes a useful supplement to teaching. It helps students transition from "verbal language" to "symbolic language" and complete the three-level cognition of concepts

5. Conclusion

This teaching uses the problem-chain teaching model to guide the entire teaching process. In deriving the sum of the first n terms of an arithmetic sequence, it utilizes students' existing cognitive levels and continuously raises reasonable and progressive questions to stimulate students to think, allowing them to derive the summation formula for the sum of the first n terms of an arithmetic sequence by themselves. It not only respects the cognitive development law of students for new knowledge, but also enables students to deeply understand the origin of the summation formula, which is conducive to students' long-term memory and application of the formula. In practical problem-solving, students can quickly judge the information in the questions and more proficiently use the summation formula to face different problems. Centering on the five core mathematical competencies, this teaching cultivates students' abilities of mathematical abstraction, logical reasoning, mathematical computing, data analysis and mathematical modeling, allowing students to achieve all-round development in the learning process.

The problem scenario of this teaching involves the restoration of ancient cultural relic buildings, which stimulates students' cultural awareness and competence, arouses students' resonance for cultural relic protection, cultivates their awareness of cultural relic protection, and at the same time allows students to have a better understanding of the long-standing Chinese culture, generate national pride. It conducts ideological education on cultural confidence for students, enhances their cultural confidence and national identity, and cultivates their sense of social responsibility. At the same time, it reveals the practical significance of our study and research on this lesson.

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