Principles of Building Intelligent Tutoring Systems for Secondary Education

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***Abstract*—The article describes an approach to creating intelligent tutoring systems using a geometry tutoring system as an example. The proposed approach assumes two modes of interacting with the system – theory tutoring and problem solving methods tutoring. The theory tutoring component allows the student to learn the material, obtain answers to various questions, and test their knowledge. In the problem-solving methods tutoring mode, the system performs a step-by-step solution checking, and provides the necessary support by answering the student's questions. This approach enables the system to store the knowledge necessary for solving problems in a formalized manner, to answer questions about the methods for solving a problem in the course of its solution, and to provide for wholistic tutoring of the theoretical concepts, including knowledge testing, which distinguishes it from other contemporary systems.**

***Keywords*—problem solving, knowledge, knowledge base, intelligent systems, intelligent tutoring system, tutoring system**

I. Introduction

In recent decades, there has been a significant increase in interest in tutoring systems in the field of school education, with particular attention being paid to the development of systems that promote independent learning.

Most recently, special attention has been paid to tutoring systems based on language models [1]. In particular, in the field of mathematics, systems that offer users automated solutions to problems have become readily available. However, despite their advantages, they do not provide sufficient support to users in the learning process. This work aims at developing an approach that focuses on interactive step-by-step guidance, aimed at effectively teaching users specific methods for solving problems rather than automatically obtaining answers.

II. State of the art

Examples of systems based on large language models (LLM) in the field of mathematics include Mathful [2], Mathos AI [3], and MathGPT [4]. However, developers of such systems also promote solutions based on the same principles in other domains, such as chemistry or physics.

Such systems are marketed as problem solvers that provide the user with a description of the solution for educational purposes. This means that they are usually designed to solve problems automatically instead of offering step-by-step support to the user, which is a notable shortcoming of systems aimed at automatic problem solving.

In general, for interactive problem solving, existing LLMs can be used as is. In the latest versions of popular models, a reasoning function has appeared, which allows the user to see the problem-solving process itself, which can help in studying the material. However, using LLMs in their pure form has its drawbacks: for example, there is no control over the complexity of the information and its presentation, which is why the solution may not correspond to the student's level of knowledge; in addition, such problems of LLMs as providing unverified information and hallucinations are widely discussed [5]. The use of LLMs and AI in the field of education is also associated with additional ethical issues, such as personal data security and possible biases [6].

Moreover, the solution provided by LLM-based problem solvers can utilize methods that diverge from ones adopted in the school curriculum. LLMs also have a tendency to generate materials that do not always correspond to curricula approved by educational institutions. This can lead to the student learning problem solving methods that are not covered by the school curriculum or learning terminology that differs from the requirements of the course they are taking.

A different approach is taken by educational systems such as Euclidea [7] and Geogebra [8]. Euclidea is an application with a set of interactive tasks for studying geometry, which offers users the ability to check one's solution and read brief explanations before each task. An interesting feature of this system is its gamification – as students complete tasks, they can earn points depending on how efficiently the task was solved.

Geogebra, on the other hand, is an educational system for various areas of mathematics, aimed at developing the skills of school-age students in the relevant subject matter. The system has a detailed and wholistic program with a set of tasks on various topics, and the tasks are classified based on the student's level of knowledge (determined by their school grade). The system includes hints, tasks that teach specific theory, and test questions for reinforcement. Additionally, the system offers integrations with other systems used in education, such as Google Classroom.

However, the drawback of these systems is that they do not offer interactive and personalized support to students at all stages of studying the material and solving problems. The user does not have the opportunity to ask questions of interest at any time, and the systems themselves do not have a knowledge base on the topics being studied, which would allow them to interactively answer such questions.

Thus, this work is aimed at eliminating the above-mentioned shortcomings in existing tutoring systems by developing an approach that focuses not so much on automatic solution of various problems and providing solutions, but rather on effective teaching of the user through interactive step-by-step guidance in solving problems using specific methods. The task providing for the ability of the system to solve arbitrary problems was not set at this stage.

III. Proposed approach

We propose to develop a system that will not only provide ready-made solutions to problems, but also perform an educational function, facilitating the solution process, rather than offering the answer immediately. For successful problem-solving, the user needs theoretical knowledge, so it is reasonable to implement two modes of working with the system:

1) Working with theory, including learning the theory and answering questions about it, as well as a testing mode.
2) Problem-solving training, in which the user is offered a problem on a given topic for solution, and the system provides support, giving explanations and hints if necessary.

We propose to create intelligent tutoring systems based on the OSTIS technology, which is focused on the development of knowledge-driven computer systems. The main principles of this technology [9] allow us to identify three key components: *knowledge base*, *problem solver*, and *user interface*, which corresponds to the traditional definition of an intelligent system [10].

As a formal basis for representing knowledge in this technology, a unified semantic network with an interpretation based on set theory is used. This representation model is called SC-code (Semantic Computer Code). The elements of the semantic network are denoted as sc-nodes and sc-connectors (sc-arcs, sc-edges). Agents described using SC-code will be called semantic agents or simply sc-agents.

This technology will help to set the necessary structure for organizing theory in the system, and with its multi-agent approach, it will allow us to implement agents that help the user to solve specific problems based on pre-formalized problems.

To ensure that the theoretical material provided by the system corresponds to educational standards, it is necessary to formalize it in the system's knowledge base, within which it is possible to relatively easily structure the material according to various characteristics: topics, correspondence to specific classes, etc. – including the ability to take into account several characteristics at the same time.

The translation of formalized knowledge into a natural language representation is proposed to be carried out using LLMs with the approach described in the work [11].

The proposed approach not only allows the use of LLMs and various classifiers, but also creates conditions for their effective integration with the advantages of the developed intelligent educational system [12]. This synergy opens up new opportunities for improving the quality of interaction with users and enhancing the educational process.

The integration of LLMs in an intelligent system based on the OSTIS technology significantly expands the functional capabilities of the intelligent tutoring system. This allows for the creation of more effective and personalized learning conditions, which represents a significant step towards improving the quality of the educational process.

Using the OSTIS technology, we can effectively store knowledge obtained during communication with the user. This will enable the formation of more personalized responses, taking into account the context and individual needs of each student. Personalization of learning promotes deeper mastery of the material and increases student motivation.

Finally, to ensure necessary support in the process of problem solving, the knowledge base must contain problems' standard solution plans in the form of a sequence of actions. The issue of automatic construction of solution plans is discussed in the work [13], but at the initial stage of prototype development, it was decided to abandon the implementation of this mechanism in favor of manual preliminary description of solutions in the knowledge base. This will allow for faster testing of the concept and minimize errors associated with automatic generation.

Thus, we propose to build the system according to the following principles:

1) A formalized representation of theoretical material in the knowledge base.
2) A formalized representation of the actions necessary to solve a problem (generated by the system automatically or prepared in advance).
3) Translation of formalized knowledge into natural language.
4) Integration with LLMs as a means of generating tests, as well as part of the pipeline for translation of formalisms into natural language, but not as a source of knowledge.
5) The presence of functionality for interactive learning of problem-solving by users.
6) The presence of a user model in the system.

Next, we will consider the structural components of the system.

A. Theory tutoring component

The theory tutoring component provides a range of functional capabilities that facilitate the mastery of theoretical material.

The system proposes to divide learning by grade and topic. During the learning process, the user will be able to:

1) **Study material on a specific topic.** Before asking the system specific questions, the user must select the topic they want to study. After that, they will be provided with a list of key concepts, theorems, properties, etc. on a specific topic.
2) **Get an answer to key questions.** The system can provide answers to individual questions that interest the user on a specific topic. The intelligent system ensures the provision of information on a range of requests, including:
   - definition of term X;
   - properties inherent to X;
   - statements related to X;
   - theorems and properties within the corresponding field.
3) Consolidate the material. The user can consolidate the material by taking a test on the topic, where the system will ask the user questions exclusively on the selected topic.

The advantage of the proposed approach is that the intelligent system will limit its answers to include only the information directly related to a specific topic. This significantly reduces the likelihood of distracting the user with extraneous aspects unrelated to the material being studied.

Thus, the student will be able to focus exclusively on the knowledge and skills necessary for a deep understanding of the subject. Focusing on relevant information promotes more effective mastery of the material and improves the quality of education. Additionally, such a targeted structure of interaction allows minimizing cognitive load, which in turn can contribute to a higher level of retention and application of acquired knowledge.

B. Problem-solving methods tutoring component

This component is proposed to be divided into two sub-components:

1) Component for solving pre-formalized problems.
2) Component for solving problems that are unknown to the system.

Within the proposed intelligent system, students are given the opportunity to practice solving problems, which is an important aspect of their educational process. Students are offered a text description of the problem, accompanied by relevant graphical material, which facilitates visualization of the problem and better understanding of the task.

In the process of working on the problem, the student has the opportunity to enter intermediate values on the graphical representation or in the associated interface. For example, in the case of a geometry tutoring system, such a representation will be a drawing, and when solving a problem to calculate the perimeter of a right triangle with known legs, it is expected that the student will first enter the length of the hypotenuse. This function allows the system to track the sequence of steps performed to solve the problem and evaluate their correctness, which is critically important for forming skills and abilities.

In addition, the system provides the opportunity to ask clarifying questions about solving the problem. The student can request information on the following aspects:

- which theorems may be useful for solving the given problem;
- what properties should be remembered;
- what formulas may be useful in the solution process;
- what needs to be calculated next.

The system also allows for clarifying the correctness of intermediate results, which promotes the student's self-control and increases their confidence in their abilities.

To implement the functionality for working with problems whose solutions are not previously known, it is critically important to create a module designed to build a solution plan for the problem. This module plays a key role in breaking down complex problems into simpler and more trivial components that do not require additional effort to solve [13].

With the help of this module, the system will be able to not only provide the user with the final answer, but also, as in the case of pre-formalized problems, offer hints that will help in the solution process. This will allow students to better understand the structure of the problem and develop analytical thinking skills.

IV. An example of the application of the proposed approach

The testing of the proposed approach is being carried out on the basis of existing developments of a tutoring system for geometry, since an extensive knowledge base on this topic was already created previously.

The system consists of three components: the user interface, the knowledge base, and the problem solver.

A. User interface

The interface of the developed system is presented in Fig. 1. The figure illustrates the key component of the system – the problem-solving component, which consists of the following elements:

1) **Natural language chat.**
   This element provides students with the ability to ask clarifying questions about solving problems. Students can request information about useful theorems, properties, necessary formulas, and the sequence of calculations. Two-way communication between the student and the system via the chat promotes a deeper understanding of the material and active involvement of students in the learning process.
2) **Drawing**, which is a visual representation of the problem, making it much easier to understand. Students can enter intermediate values on the drawing, for example, the length of the hypotenuse in a problem of calculating the perimeter of a right triangle. This function allows the system to track the sequence of steps performed and evaluate their correctness, which is critical for developing problem-solving skills.
3) **Data entry field.**
   This element is indicated by an arrow in the figure. This element allows students to enter the necessary values directly on the drawing, which improves interaction with the system.

B. Knowledge base

As part of the previously developed geometry system, an extensive knowledge base was created, which includes Euclidean geometry, various theorems, and basic concepts. This knowledge base serves as the foundation for teaching students and forming their mathematical skills. In connection with the need to adapt the system to the educational standards of secondary education, it was decided to supplement the existing platform with subject areas corresponding to different school grades.

This approach has several significant advantages. It allows the system to more accurately navigate through theorems and corollaries, which in turn promotes more effective problem-solving, taking into account the level of knowledge of the students. For example, for 7th-grade students, a simple and accessible solution to a problem will be proposed, corresponding to their level of preparation. This will provide them with the opportunity to gradually master the material and develop basic skills. In turn, for 9th-grade students, the system will be able to offer more complex hints and recommendations, corresponding to their higher level of knowledge. This will create conditions for in-depth study of geometry, which will help students develop critical thinking and analytical abilities. The possibility of a differentiated approach to learning is a key aspect that contributes to the individualization of the educational process and increases its effectiveness.

Thus, this approach has several advantages:

1) Promotion of more effective problem-solving, taking into account the level of knowledge of the students.
2) Adaptation of the system to the user's knowledge.
3) Gradual mastery of the material by students.
4) Development of critical thinking and analytical abilities in students.

C. Problem solver

As part of the developed system, a problem-solving verification agent was integrated, which plays a key role in the educational process. The system's knowledge base was supplemented with formalized problems from various areas of geometry, as well as theorems necessary for performing specific actions. This agent actively uses these formalized problems to evaluate user solutions, providing them with drawings to fill in.

The verification agent monitors the correctness of the user's problem-solving, comparing the user's actions with standard formalized problems. If errors are detected during the solution process, the agent highlights them in red on the drawing, indicating specific areas where inaccuracies were made.

When the user encounters difficulties or does not know how to continue solving the problem, the system offers hints without completely revealing the correct answer. For example, if a student tries to immediately indicate what the area equals to, ignoring the need to calculate the height, the agent draws attention to this and reports that necessary data is missing to complete the solution.

Fig. 2 shows an example of a formalized problem statement.

Fig. 3 shows a formalized sequence of actions for solving a problem with necessary justifications.

In Fig. 4, a construction in the knowledge base is presented, which is the result of performing one of the actions involved in solving the problem.

V. Conclusion

In this paper, we discussed an approach for creating an intelligent tutoring system that effectively integrates the teaching of theoretical aspects with the development of practical problem-solving skills. The system creates conditions for students to independently master the material and improves their skills.

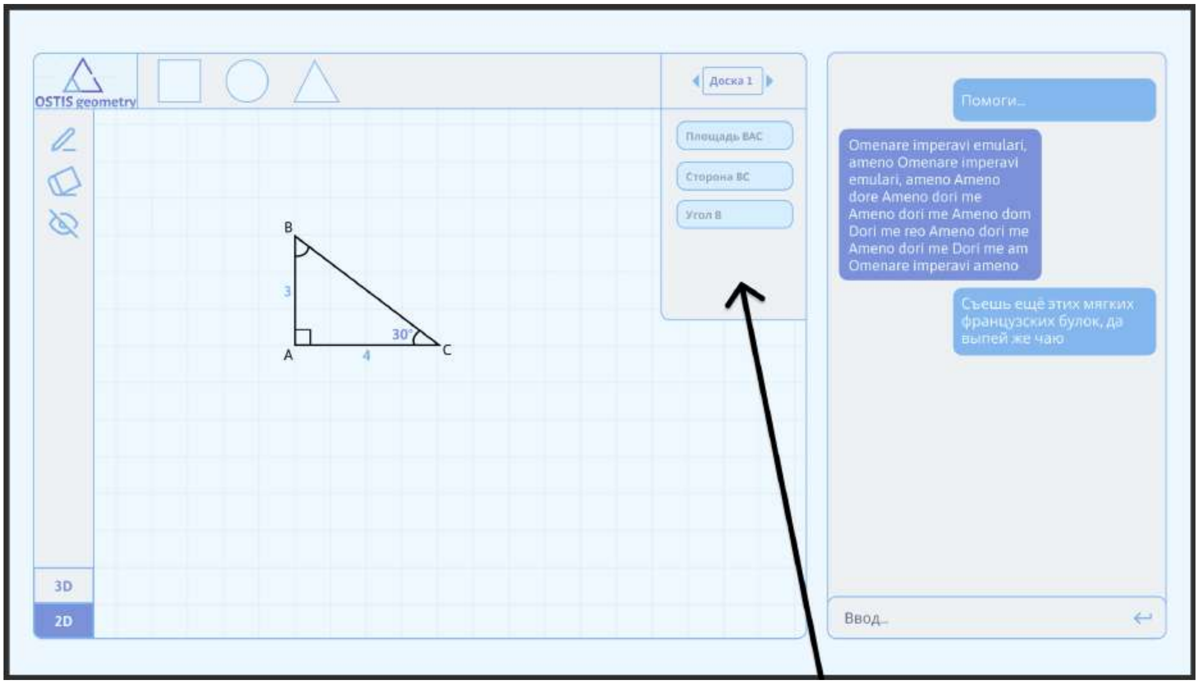

Figure 1. User interface of the intelligent tutoring system for geometry

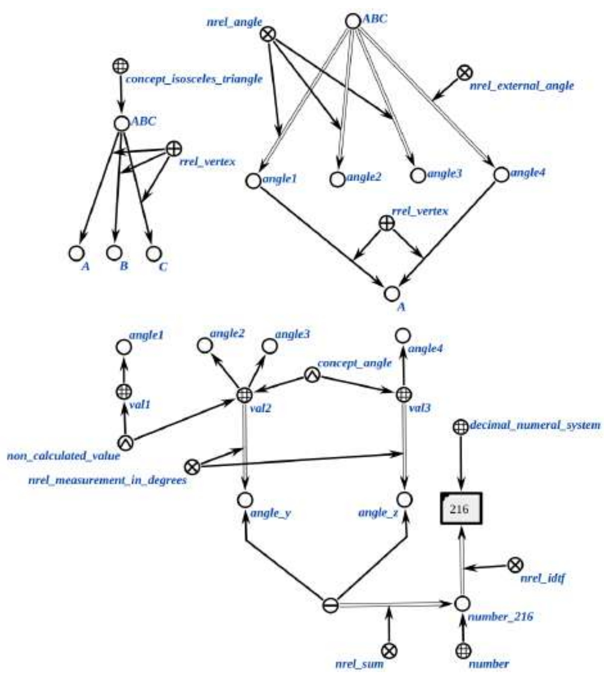

Figure 2. Formalization of a problem statement

The system provides users with the opportunity to solve complex problems step by step, breaking them down into simpler parts, which promotes a deeper understanding of the theory and forms a conscious approach to the solution process. Students can ask clarifying questions and receive recommendations on necessary theorems and formulas, which significantly improves their understanding of the subject matter.

Additionally, storing knowledge about the user in a knowledge base will allow the system to generate more accurate and contextualized responses, making the learning process more adaptive and effective. Thus, this intelligent tutoring system represents a significant step towards improving the quality of education, successfully combining theoretical knowledge with practical problem-solving skills and allowing students to develop independently.

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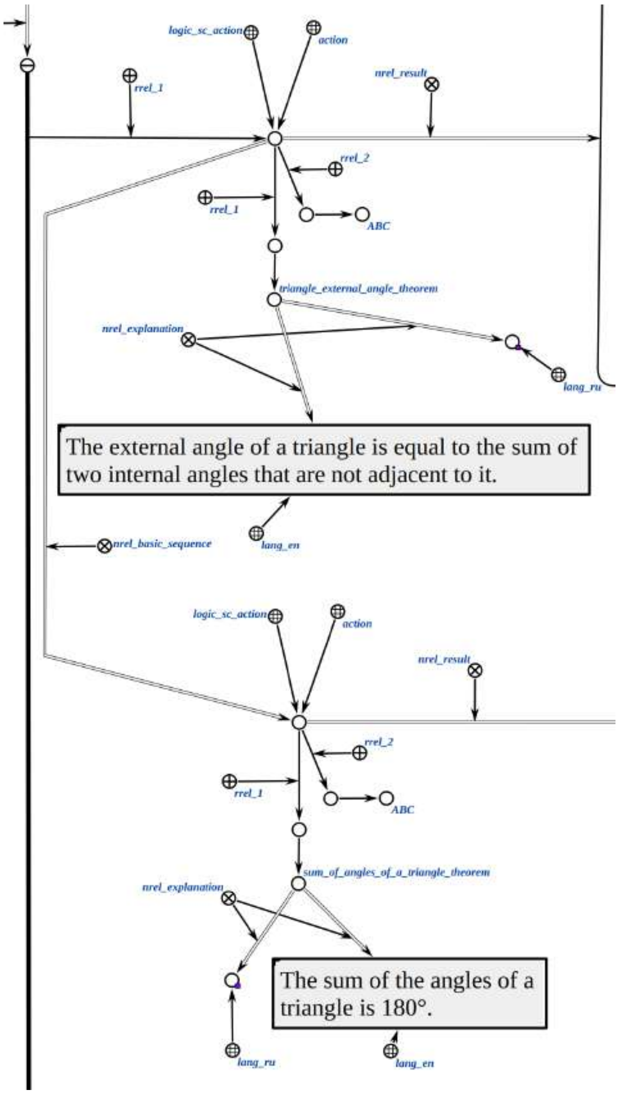

Figure 3. A formalized sequence of actions for solving a problem

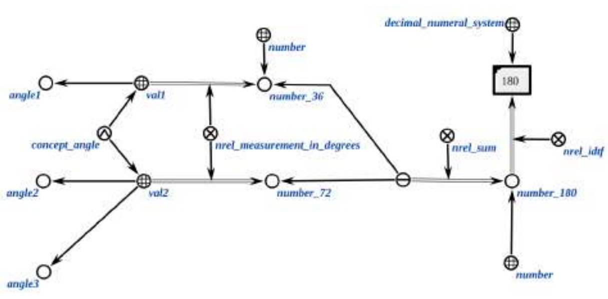

Figure 4. The construction that is the result of performing one of the actions involved in the solution

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ПРИНЦИПЫ ПОСТРОЕНИЯ ИНТЕЛЛЕКТУАЛЬНЫХ ОБУЧАЮЩИХ СИСТЕМ ДЛЯ СРЕДНЕГО ОБРАЗОВАНИЯ

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В статье описывается подход к созданию интеллектуальных обучающих систем на примере обучающей системы по геометрии. Предлагаемый подход подразумевает два режима работы системы – обучение теории и обучение методам решения задач. Компонент обучения теории позволяет изучить материал, получить ответы на различные вопросы по теме и протестировать полученные знания. В режиме обучения решению задач система осуществляет поэтапную проверку решения и поддержку, отвечая на вопросы ученика. Данный подход обеспечивает способность системы хранить необходимые знания по решению задач в формализованном виде, отвечать на вопросы по методам решения задачи в процессе ее решения, осуществлять комплексное обучение теоретическим аспектам, включая тестирование знаний, что отличает его от существующих систем.

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