Developing students computational thinking with a recursive polydisciplinary approach

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Abstract. The formation and development of many of the competencies identified in the Federal State Educational Standard of Higher Education cannot be fully implemented within a separate discipline. For example, to develop a high level of computational thinking is extremely important for modern specialists in engineering, technical and natural sciences. The disciplinary model of educational programs of higher educational institutions does not allow purposeful and effective development of this student’s competence. In this regard, it is of interest to create new organizational and meaningful approaches to training specialists without a significant restructuring of the traditional educational process. The purpose of the study is to substantiate a recursive-polydisciplinary approach in the special construction of the content and organization of student training on the principles of clustering of several disciplines. On the example of three disciplines (Programming, Computational Methods, Information Technologies in Education), a cluster model for teaching students to be trained in "Mathematics and Computer Science" was designed and implemented using cognitive and didactic techniques and methods. The recursive-polydisciplinary approach has shown a high efficiency of teaching students in the considered disciplines of the cluster. An analysis of the experimental teaching of students of the Institute of Mathematics and Fundamental Informatics of the Siberian Federal University in the context of the implementation of the proposed cluster model over the past few years has shown the possibility of purposeful formation and development of their computational thinking. The proposed recursive-polydisciplinary approach can be used to create clusters of disciplines that allow their meaningful collaboration and form given general groups of student’s competencies.

1. Problem and purpose

Competence maps of educational programs (FSES HE) contain competencies that are formed by a number of disciplines during the entire period of students' training. Due to the autonomy of the basic courses of the traditional discipline model of the educational process, the interdisciplinary links are difficult to provide, and sometimes impossible. In this regard, it is of interest to create new organizational and meaningful approaches to strengthening interdisciplinary linkages for more effective and expedient formation of certain groups of student’s competencies.

For example, one of the core competencies - the development of computational thinking - is the most important characteristic of a modern specialist, which is necessary for his professional growth [1]. By computational thinking, following J. M. Wing is meant "the thought processes involved in formulating..."
a problem and expressing its solution(s) in such a way that a computer – human or machine – can effectively carry out” [2]. Computational thinking is a superdisciplinary concept; it is formed in the process of studying a variety of disciplines - mathematics, natural science, engineering, etc. [3]. Its formation and development begins at school. Further, many disciplines of university curricula contribute to the development of student’s computational thinking. Possibly the most significant contribution to the development of this competence among students of engineering and natural sciences is made by the disciplines related to mathematical modeling, computational methods and programming. In this regard, it seems relevant to create a special cluster of such disciplines, which provides the best option for the process of interdisciplinary relationships.

The purpose of the study is to substantiate a recursive-polydisciplinary approach in the special construction of the content and organization of student training for the development of their computational thinking in the cluster of disciplines "Computational Methods - Programming - Information Technologies in Education".

2. Literature review
The term "computational thinking", to which J. M. Wing drew attention in the paper [4], is not well-established and has numerous interpretations. A detailed review of existing definitions and correlation with the terms “digital literacy”, “digital competence”, etc. is presented in [5], [6], [7]. Analysis of foreign sources shows that there are three approaches to clarifying the essence of this concept [8]:

- computational thinking as a cognitive thought process;
- computational thinking as a hybrid of other ways of thinking (a type of analytical thinking associated with mathematical, algorithmic, logical, systemic, parallel thinking);
- computational thinking as the application of Computer Science methods to simulate processes studied in other disciplines.

Among domestic sources, the definition of L.L. Bosova, D.I. Pavlov should be noted, which considers computational thinking as “a set of requirements for a person who understands the possibilities of information technologies, who is able to use them effectively, who sees new areas of their application in solving complex problems in various fields of activity” [9].

The current study using the first of the listed approaches considers computational thinking as a set of mental tools and concepts from the field of computer science that expand the mental capacity of a person using abstractions and help people solve problems in the form of a sequence of steps or algorithms. In this case, the author's concept of "multidimensional algorithmic thinking" (as a type of computational thinking) and methods of its development is taken into account [10].

In the 17th century, the importance of interdisciplinary connections was noted by the outstanding teacher Ya. A. Komensky, who believed that "everything that is in mutual connection should be taught in the same connection" [11]. Interdisciplinary communications are implemented through the formation of a professional thesaurus, which is common for the selected disciplines, the development of generalized skills and abilities, and the solution of complex interdisciplinary problems. The means of implementing intersubject connections are the electronic information and educational environment of the university, intersubject educational modules, intersubject projects. So in [12], an example of the implementation of an interdisciplinary project with methodological support in the chain of disciplines "Design of Information Systems - Project Management - Databases" is considered. STEM education, which includes interdisciplinary subject content and a problem-oriented approach to teaching, is now becoming common [13].

3. Methods and methodological framework
The research methodology is based on interdisciplinary, cluster and recursive approaches to teaching.
In modern pedagogy, interdisciplinary connections are considered as an effective mechanism for the formation of professional competencies, a necessary condition for the development of cognitive activity and independence of students.

The cluster approach seems to be an attractive mechanism for the collaboration of several disciplines to strengthen intersubject connections [14]. The creation of a cluster of disciplines on the basis of the targeted intersection of their content lines will make it possible to enrich and systematize subject knowledge in a multifaceted way; it is advisable to form the given groups of student’s competencies. The development of computational thinking as a dynamic, multicomponent and multifunctional cognitive component of the mind can serve as a system-forming factor in organizing a cluster of several disciplines.

For the development of computational thinking in a cluster of disciplines, it is necessary to define the outlines of a cluster work program that includes all the traditional components: goals, content, teaching methods and means, learning control. It is important to take into account, when preparing students, the motivated application of the knowledge gained in complex tasks, educational and research projects. For these purposes, the recursive strategy for the implementation of projects to create innovative electronic teaching aids in the studied disciplines is optimal [15]. The recursive principle of teaching: "I create a teaching tool by which I learn" provides the student with active knowledge, experience of their application in real and useful software products for themselves and others. This approach significantly increases the motivation of students for successful learning and enhances their interest in future professional activities. The range of educational and self-educational artifacts created can be quite wide: from conceptual maps to interactive textbooks, which depends on the level of development of digital competence of a particular student and his individual educational and psychological preferences.

4. Results and discussion

Like any thinking, computational thinking is developed in the process of human activity through the assimilation of thinking techniques, their independent application and transfer to new situations. The formation of computational thinking is determined by the combination of the following thinking strategies: algorithmization, abstraction, decomposition, generalization, evaluation. Their development among students to be trained in "Mathematics and Computer Science" at the university begins with the study of the basic discipline "Programming" in the 1-2 years.

Discipline "Computational Methods" (3rd year of study) is aimed at the formation of a high level of mathematical computational culture and scientific outlook of students. It has a distinctive practice-oriented character, is the basis for the study of subsequent disciplines, such as "Parallel Programming", "High Performance Computing", "Mathematical Modeling", serves as a basic tool for scientific research in the field of computational mathematics and computer science. For the independent implementation of computational methods, students use the skills acquired in the study of programming languages (C++, Delphi).

Practice shows that it is useful for future mathematicians to gain experience in the development of training systems, since many of them in the future associate their professional activities with education. For these purposes, an elective course "Information Technologies in Education" is provided in which students are trained in the design and testing of new tools, methods and models of the modern organization of the educational process, acquire skills in the development of electronic textbooks and educational portals [16].

When building a model of an interdisciplinary cluster in the disciplines "Programming" - "Computational Methods" - "Information Technologies in Education", the development of computational thinking of students and, as a result, the development of professional competencies of future specialists in the direction of "Mathematics and Computer Science" was taken as a general educational goal presented in table 1.
Table 1. List of implemented competencies.

| Discipline                          | Competence                  | Competence content                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|------------------------------------|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Programming                        | General teaching competence| Able to find, analyze, implement software and put mathematical algorithms into practice, including the use of modern computing systems.                                                                                                                                                                                                                                                                                                                                                           |
|                                    | GTC -4                      | Able to solve standard professional tasks on the basis of information and bibliographic culture using information and communication technologies, including domestic producers, and taking into account the basic requirements of information security.                                                                                                                                                                                                                                                                                                     |
| Computational methods              | GTC-1                       | Ready to use fundamental knowledge in the field of mathematical analysis, complex and functional analysis, algebra, analytical geometry, differential geometry and topology, differential equations, discrete mathematics and mathematical logic, probability theory, mathematical statistics and random processes, computational methods, theoretical mechanics in the future professional activities.                                                                                                                                        |
| Information Technologies in Education| Professional competence/   | Able to apply basic knowledge of mathematical and natural sciences, programming and information technologies in research activities.                                                                                                                                                                                                                                                                                                                                                           |
|                                    | PC-1                        | Able to use modern methods of developing and implementing algorithms based on programming languages and software packages.                                                                                                                                                                                                                                                                                                                                                                   |
|                                    | PC-2                        | Able to create and research mathematical models in natural sciences, industry and business, taking into account the capabilities of modern information technologies, software and computer technology.                                                                                                                                                                                                                                                                                                                   |

Within the framework of a polydisciplinary approach, all disciplines remain within their own methodological principles; however, the cooperative complex of knowledge is mutual and cumulative. Learning using cognitive technologies that take into account the peculiarities of the development of modern students is considered as a strategic direction of education. The leading role is given to activity methods and the use of blended learning using electronic courses.

Within the cluster, e-courses are used, which include the following cognitively visualized learning tools: interactive concept maps, visual simulators, lectures, simulators, dynamic tests simulators, banks of test questions, classic interactive electronic tests with multimedia elements, sets of UML diagrams and etc. The variety of teaching aids allows the teacher, by creating a multivariate reproduction of the content, to design a kind of transformer textbook [17], corresponding to their intentions and preferences of the student. With such a multivariate structural composition of the content, it becomes possible for each student to choose a convenient and preferable format for presenting information.

The scientific concept of recursive technology is the creation and application of a variety of intelligent electronic didactic tools developed by students as part of an elective course. Learners realize their educational needs as an individual project not just in the process of “consuming” digital educational resources, but also “producing” their own resources, which are immediately put into the educational process of the disciplines included in the cluster. At the same time, students deepen their knowledge in programming languages and develop creative thinking by inventing author's models of artificial intelligence for the educational process. This factor enhances the motivational component of the learning and self-learning process and enables to achieve the highest possible quality of individualization of learning. Clustering several basic academic disciplines (polydisciplinarity) on the basis of the targeted intersection of their content lines allows enriching and systematizing discipline knowledge in many ways, and as the main effect it works on the formation and development of students' computational thinking.

The recursive polydisciplinary approach has shown a high efficiency of teaching students in the considered disciplines of the cluster. When studying computational methods, students use mental schemes and programming skills; in programming classes they code computational algorithms and
create electronic programming textbooks; in the process of teaching the course "Information Technologies in Education" they master innovative methods of building teaching aids (electronic tutors, knowledge control programs) on computational methods and programming.

5. Conclusions
The proposed recursive polydisciplinary approach allows the formation of clusters of disciplines that improve the quality of interdisciplinary relationships and optimize the formation of specified groups of general cultural and basic discipline competencies among university students. The analysis of the experimental teaching of students of the Institute of Mathematics and Fundamental Informatics of the Siberian Federal University over the past several years, in the context of the implementation of the proposed cluster disciplinary model, showed the possibility of purposeful formation and development of their computational thinking.

The cluster of disciplines has a didactic advantage over traditional autonomous disciplines due to the following:

- the shared set of learning goals for disciplines included in the cluster;
- changing the learning strategy from the paradigm "accumulation of knowledge for solving future problems" to the paradigm "solving problems by mastering the necessary knowledge";
- the cumulative effect of learning, allows the teacher to achieve the desired educational results with minimal time costs;
- a motivational mechanism for the implementation of a complex task or project that provides certification of the student's knowledge in all disciplines of the cluster;
- more convenient implementation of conditions for satisfying the self-education needs typical for digital generation Z.

Thus, the proposed recursive-polydisciplinary approach makes it possible to create clusters of disciplines to achieve higher results of discipline learning and optimal formation and development of the required competencies. The materials of the article are of interest for those who are in charge of educational process management, as well as for teachers who want to use the potential of interdisciplinary connections.

References
[1] Davies A, Fidler D and Gorbis M 2020 Future Work Skills
[2] Wing J M 2017 Computational thinking’s influence on research and education for all Italian J. of Educational Technology 25(2) 7-14 doi: 10.17471/2499-4324/922
[3] Khenner E K 2016 Computational thinking The Education and Science J. 2 18-33
[4] Wing J M 2006 Computational thinking Communications of the ACM 49(3) 33-5
[5] Grover S and Pea R. 2013 Computational thinking in K–12: A review of the state of the field Educational Researcher 42(1) 38-43
[6] Bocconi S, Chiocchieri A, Dettori G, Ferrari A and Engelhardt K 2016 Developing computational thinking in compulsory education – Implications for policy and practice EUR 28295 EN doi:10.2791/792158
[7] Yadav A, Sands P, Good J and Lishinki A 2018 Computer Science and Computational Thinking in the Curriculum: Research and Practice Handbook of Information Technology in Primary and Secondary Education pp 1-18 doi: 10.1007/978-3-319-53803-7_6-1
[8] Klunnikova M M 2020 Development of Computational Thinking in the process of Teaching the Discipline “Computational Methods” (Krasnoyarsk) p 24
[9] Bosova L L and Pavlov D I 2019 “New” literacy and the formation of its components in teaching Computer Science in primary school Science and School 3 156-66
[10] Pak N I, Stepanova T A, Bazhenova I V and Gavrilova I V 2019 Multidimensional algorithmic thinking development on mental learning platform J. Sib. Fed. Univ. Humanit. soc. sci. DOI:
[11] Komenskiy Ya 1940 Didactic principles (Moscow:Uchpedgiz) p 92
[12] Ignatoova I G, Balashov A G and Sokolova N Yu 2014 Interdisciplinary projects as a way of developing competencies in implementing educational programs Higher Education in Russia 5 86-93
[13] Holmlund T D, Lesseig K and Slavit D 2018 Making sense of “STEM education” in K-12 contexts IJSTEM Ed 5, 32 https://doi.org/10.1186/s40594-018-0127-2
[14] Sokolova E I 2014 The term “educational cluster” in the conceptual field of modern pedagogy Lifelong Education: the XXI Century 2(6) 153-60
[15] Bazhenova I V and Pak N I 2016 Projective-recursive learning technology in student-centered education Pedagogical education in Russia 7 7–15
[16] Klunnikova M M and Pak N I 2018 Dual interdisciplinary approach to teaching Computational Methods and an elective course “Information Technologies in Education” Vestnik of the National Pedagogical University named after Abai. Series: Physics and Mathematics 4(64) 161-5
[17] Bazhenova I V and Pak N I 2019 Development of an electronic textbook-transformer for teaching programming based on the student’s self-cognitive activity Vestnik of Moscow City University. Series: Informatics and Informatization of Education 1(47) 20-8