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IDENTIFICATION OF INTRASUBJECT CONNECTIONS OF THE SCHOOL PHYSICS COURSE USING A COMPUTER

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Abstract:
The method of determining the semantic proximity between the topics of the school physics course for grades 10-11 is considered in order to identify intra-subject relationships. For each pair of topics, the proximity cosine measure of key concepts and Dice measure, are calculated. The computer program written in ABCPascal was used, which sequentially iterated through the terms from the file t1.txt and compared them with each term from the file t2.txt. This allowed us to calculate the strength of the semantic connection between any two topics. The logical connection between some concepts is taken into account. A graph has been obtained showing the connections between 22 topics of the school physics course.

Keywords: *intrasubject connections, didactics, key concepts, training, physics course, semantic proximity, textbook.*

Introduction

The school physics course is a multidimensional system object, between the various elements of which there are numerous semantic connections, often called intrasubject. This is manifested in the fact that the same terms, scientific concepts, ideas, models, and approaches are used to study various issues. By identifying these connections, it will be possible to build a model of a school physics course and, possibly, optimize its structure.

The problem of identifying intra-subject connections in the physics course and their actualization to improve the systematic thinking and knowledge of students was dealt with by various methodologists [1-4]. They used a variety of methods involving qualitative and quantitative analysis of educational texts in physics. For example, N.F. Iskanderov identified 10 types of intrasubject connections [1]. K.A. Popov and P.A. Strochilov in paper [2] considered the role of intrasubject connections in teaching disciplines with a concentric structure and their actualization to improve learning efficiency. T.N. Gnitetskaya proposed a theory of intra-subject connections based on the application of the graph method, which made it possible to determine the number and volume of these connections for various physical laws, and optimize the structure of the general physics course [3]. Obviously, the authors of various textbooks also take into account the proximity degree of the topics under consideration.

Due to the vagueness of the problem, these approaches have a significant drawback, which is the need for the active participation of an expert, who often acts "on a whim", which increases the subjectivity of the results obtained. It is often impossible to list which factors and to what extent are taken into account when determining the similarity of texts and identifying semantic links between them. Taking into account only physical laws (and not concepts!), as done in [4], does not allow to identify all connections. Therefore, the resulting model of the physics course is very approximate. All this determines the relevance of the study.

To obtain more accurate and objective results, the method of automatic (computer) determination of the meaningful proximity degree of texts based on the consideration of concepts should be used. In this case, each text is replaced by a matrix of the word frequencies included in it, corresponding to some vector in the semantic N-dimensional space. The proximity measure of texts T_A and T_B is the cosine of the angle between the corresponding vectors; it varies from 0 for orthogonal vectors to 1 for co-directional vectors when T_A and T_B are identical [5-7]. Other similarity criteria can also be used, for example, the Dice measure [5, 6].

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The purpose of the research: using objective methods, to establish the degree of semantic proximity between the topics of standard school textbooks [7, 8], to identify intra-subject connections and build a graph model of the physics course. To achieve it, it is necessary to solve the following tasks: 1) to develop a method for assessing the similarity of educational texts; 2) to create a computer program that calculates the degree of proximity between texts; 3) to apply the proposed method to a school physics course and analyze the results. **The methodological basis of the research** is the work of scientists: N.K. Andrievskaya [5], S.H. Bermudez [10], P.E. Velikhov [6], L.A. Kuznetsov and V.F. Kuznetsova [11], Nguyen Ba Ngoc, A.F. Tuzovsky [12], A.Sh. Suleymanov [13] (semantic similarity of texts), T.V. Efimova [14], O.A. Turbina and O.A. Savelyeva [15] (textual links), T.N. Gnitetskaya [3, 4], N.F. Iskanderov [1], K.A. Popov, P.A. Strochilov [2] (intra-subject relations), I. Y. Moiseeva [16] (quantitative linguistics).

Discussion of the research problem

T.V. Efimova's article [14] is devoted to network modeling of a literary text, which provides: 1) identification of connections between its elements; 2) presentation of connections in a convenient form (i.e. creation of text model); 3) study of the text patterns using the resulting model. At the same time, it is considered that there is a semantic connection between two sentences, if both indicators of connectivity are present in them, which can be: 1) identical nouns or a noun and a pronoun replacing it; 2) synonyms or words of the same root; 3) nouns with a paradigmatic connection between them (for example, charge – current). The more indicators of connectivity, the higher the strength of the semantic connection [14]. This approach can also be applied to educational texts. At the same time, the situation is simplified, since: 1) in text, all connections are explicitly indicated; 2) standard scientific terminology is used; 3) pronouns are rarely used.

Due to the considerable volume of physics textbooks [8, 9], the problem of determining the connections between topics becomes time-consuming. It is also complicated by the use of a large number of mathematical terms ("equal", "add", "multiply") and universal words such as "moves", "acts", "consider", "therefore", "means", etc. We are interested in the logical and semantic connections between topics in terms of studying new phenomena, assimilation of concepts, ideas and theories related to physics. Therefore, it is proposed to apply the keyword method: divide the text into topics in which related phenomena are considered, and for each of them write out keywords expressing the essence of the educational material. If the text includes formulas, then it is necessary to write out the concepts corresponding to the quantities included in the formulas.

Two topics will be considered semantically related if: 1) in each of them there are identical concepts, or the concepts C_1 and C_2 logically related when C_2 is included in the definition of C_1; 2) the same or similar models, approaches, and reasoning are used. In the text, the reported information is presented explicitly, without any allegories and hints, therefore, to establish the semantic proximity of the texts T_A, T_B, T_C, ... it is enough to assess the coincidence degree of scientific vocabulary, taking into account the logical connections between the concepts.

Within the framework of the applied approach, the compared texts T_A and T_B are represented by lists of keywords A and B indicating the number or frequency of their use. This allows the use of statistical methods to obtain a quantitative assessment of the text similarity. Combining sets of key concepts forms the thesaurus with volume $N = N(A \cup B)$. The formal representatives of lists A and B are the vectors $\vec{a}(a_1, a_2, ..., a_N)$ and $\vec{b}(b_1, b_2, ..., b_N)$, the components of which are the number or frequency of keywords (some of them are equal to 0). Then the degree of meaningful proximity between texts T_A and T_B (or lists A and B) is determined by the cosine of the angle between these vectors in N-dimensional space [5, 6]:

$$K(A,B) = \frac{a_1 b_1 + a_2 b_2 + ... + a_N b_N}{|a| \cdot |b|}, \quad |a| = \sqrt{a_1^2 + a_2^2 + ... + a_N^2}, \quad |b| = \sqrt{b_1^2 + b_2^2 + ... + b_N^2}.$$

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If the lists A and B do not have common words ($A \cap B = \varnothing$), then the vectors $\vec{a}$ and $\vec{b}$ are orthogonal, K(A, B)=0. The semantic proximity of text documents in information retrieval systems is calculated in a similar way [11-13].

Another criterion for the semantic similarity of texts is the Dice measure [5, 7]:

$$D(A,B) = \frac{2N(A \cap B)}{N(A) + N(B)},$$

where $N(A \cap B)$ is the number of concepts that are simultaneously included in lists A and B, $N(A)$ – the number of unique concepts in list A. This does not take into account the number of particular term mentions in the educational text, but only the fact of its presence. This will allow you to identify texts with similar sets of key concepts.

The results of the research

In order to determine the semantic proximity of two lists A and B placed in files t1.txt and t2.txt, a special program Svyazi.pas is used, written in ABCPascal. Based on the known amounts of word usage, it calculates the frequencies, and then sequentially iterates through the terms from the file t1.txt and compares them with each term from the file t2.txt. If the terms match (for long Russian words, the last 2 letters are discarded), then their frequencies a_i and b_j are multiplied and the results are summed up. The program outputs in the output file a list of key terms that occur simultaneously in these files, as well as the cosine measure of proximity K(A, B) and the Dice measure D(A, B).

To correctly determine the text proximity, it is necessary to take into account the logical connection between some concepts. The program contains two arrays w1[i] and w2[i], which contain pairs of logically related concepts, for example: velocity – acceleration, vibrations – wave, energy – intensity, energy – power, neutron – nucleon, microparticle – particle, charge – current, electromagnetic – electric, etc. (total M=33 pairs). If in the file t1.txt the word w1[i] occurs a_i' times, and in the file t2.txt – the corresponding word w2[j] occurs b_j' times, then the computer calculates the product $0{,}75\,a_i' b_j'$ and adds it to the numerator and denominator of the fraction in the formula for K(A, B). We have:

$$K(A,B) = \frac{a_1 b_1 + a_2 b_2 + ... + a_N b_N + 0{,}75\,(a_1' b_1' + a_2' b_2' + ... + a_M' b_M')}{|a| \cdot |b| + 0{,}75\,(a_1' b_1' + a_2' b_2' + ... + a_M' b_M')},$$

where M – the number of pairs of concepts from lists A and B connected logically, $a_i' b_i'$ – the product of the quantities of the *i*-th pair. From similar reasoning, the corrected Dice measure is calculated:

$$D(A,B) = \frac{2N(A \cap B) + 0{,}75N(A' \cap B')}{N(A) + N(B) + 0{,}75N(A' \cap B')},$$

where $N(A' \cap B')$ – the number of pairs of logically related concepts that are simultaneously included in lists A and B.

To study the intra-subject relationships of the school physics course for grades 10 and 11, the following method was used:

1. In physics textbooks [8, 9] we identify topics containing sets of sequentially arranged paragraphs that address related issues (for example, electrostatic phenomena). We take into account the generally accepted division of textbooks into topics, but if necessary, the paragraphs are rearranged and combined. The volumes of some topics differ by 4-5 times.

2. We divide each topic into fragments of 3 pages; from each fragment (text with drawings) we identify 6-7 key concepts, knowledge of which is necessary for understanding the educational text.

3. For each fragment, we write out formulas and create a verbal description of them (encoded with a verbal code). For example: $I = U / R$ => "the current is equal to the voltage divided

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by the resistance of the circuit section". For each topic, we create a text file (for example, tema12.txt, where 12 is the topic number), containing 20 to 40 key concepts and verbally encoded formulas.

4. Using the program TextAnalyzer.exe (downloaded from the Internet) for each topic, we create the list of key concepts with an indication of the number of their occurrences. We put it in a file like t-12.txt. The total number of mentions of key concepts in each topic is from 40 to 200.

5. We remove universal words and simple mathematical terms from the lists (add, subtract, multiply, divide, square, root); leaving vector, module, projection, sine, etc. We convert adjectives and verbs into nouns (to diffract => diffraction, to interfere => interference, molar => mole, nuclear => nucleus, core), and the words of the same root (helium and antihelium, interaction and action) are considered equivalent. The concepts of "force", "current strength" and "optical force" refer to different phenomena and are not related, while the terms "wave" and "wavelength" are.

6. Using the program Svyazi.pas for each pair of files (for example, t-12.txt and t-18.txt) we calculate the proximity measures $K(T_{12},T_{18})$ and $D(T_{12},T_{18})$. We get the matrix of connections of the school physics topics; based on it we draw a graph of connections.

As result of the analysis of textbooks for grades 10 and 11 [8, 9], the following 22 topics of the school physics course were identified: A) MECHANICS: 1) Kinematics; 2) Dynamics; 3) Conservation laws; 4) Static; B) MOLECULAR PHYSICS AND THERMODYNAMICS: 5) Fundamentals of molecular kinetic theory; 6) Temperature. The state equation of an ideal gas; 7) Solid, liquid and gaseous bodies; 8) Fundamentals of thermodynamics; C) ELECTRODYNAMICS: 9) Electrostatics; 10) The laws of direct current; 11) Current in various media; 12) The magnetic field. Electromagnetic induction; 13) Mechanical vibrations (refers to mechanics); 14) Electromagnetic oscillations; 15) Mechanical waves (refers to mechanics); 16) Electromagnetic waves; D) OPTICS: 17) Optics; E) SPECIAL THEORY OF RELATIVITY: 18) The special theory of relativity; F) PHYSICS OF THE MICROCOSM: 19) Radiation and spectra; 20) Light quanta; 21) Atomic physics. Physics of the atomic nucleus; 22) Elementary particles. In most cases, the names and content of the topics coincide with the generally accepted ones. The paragraph "Interference of mechanical waves" was moved by us from the topic "Optics" to the topic "Mechanical waves".

As a result of using the above method, a square matrix of 22 x 22 connectivity coefficients was obtained (Table 1). On the right above the diagonal, the coupling coefficients K(A,B) are presented; on the left below the diagonal, the corrected Dice measures D(A,B). For example, the cosine measure of the semantic proximity of topics 13 and 15 is $K(T_{13},T_{15}) = 0.44$, and the Dice measure $D(T_{13},T_{15}) = 0.46$, the average value is 0.45. Sometimes K and D are very different, for example: $K(T_1,T_{12}) = 0.04$, $D(T_1,T_{12}) = 0.17$. This means that the sets of key concepts partially coincide, but, taking into account the amounts of their use, topics 1 (Kinematics) and 12 (Magnetic field. Electromagnetic induction) are very far from each other. The resulting matrix (Table 1) allows us to calculate the average coefficient of proximity between any two topics (lists of key concepts): Similarity(A, B) = (K(A, B) + D(A, B))/2, get a triangular matrix and build a graph of connections (Fig. 1). It follows that the vast majority of topics in the school physics course are related to each other; the magnitude of Similarity(A, B) lies in the range [0; 0.6].

The computer program Svyazi.pas also provides a list of key concepts that occur simultaneously in the compared topics. As an example, consider the relationship between the topics 12 (Magnetic field. Electromagnetic induction) and 14 (Electromagnetic oscillations), which is due to the following concepts that play the role of connectivity indicators: vortex, inductance, induction, Lenz, magnetic, voltage, area, field, flow, self-induction, force, current, sine, current, EMF, induction EMF, electromagnetic, electric, electronic, energy, wave ~ vibrations, flux ~ magnetic induction, magnetic ~ magnetic induction, electromagnetic ~ magnetic, EMF ~ voltage, electric field strength ~ voltage, charge ~ current ($Similarity(T_{12},T_{14}) = 0.53$). The sign "~" means that these concepts are logically related, that is, one is included in the definition of the other.

Table 1. The strength of the semantic connection between the 22 topics of the physics course.

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	10 класс											11 класс										
	Механика				МКТ+Т				Электродинамика								Опт.	ЧТО	Физика микромира			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	1	0,46	0,44	0,23	0,3	0,19	0,05	0,04	0,12	0,06	0,34	0,04	0,26	0,04	0,18	0,04	0,11	0,48	0,01	0,13	0,01	0
2	0,3	1	0,53	0,7	0,16	0,09	0,01	0,01	0,23	0,06	0,26	0,26	0,48	0,07	0,07	0,04	0,07	0,2	0,01	0,04	0,13	0,12
3	0,45	0,41	1	0,48	0,36	0,34	0,04	0,55	0,41	0,24	0,25	0,18	0,58	0,28	0,26	0,18	0,1	0,39	0,07	0,52	0,25	0,12
4	0,1	0,16	0,28	1	0,1	0,08	0,08	0,1	0,22	0,04	0,14	0,22	0,35	0,07	0,04	0,03	0,03	0,06	0,01	0,1	0,09	0,1
5	0,13	0,19	0,26	0,21	1	0,6	0,23	0,32	0,18	0,12	0,2	0,12	0,2	0,14	0,14	0,14	0,09	0,35	0,09	0,25	0,33	0,19
6	0,11	0,15	0,23	0,15	0,6	1	0,48	0,51	0,11	0,09	0,24	0,04	0,18	0,14	0,13	0,09	0,04	0,22	0,04	0,25	0,17	0,06
7	0,06	0,05	0,03	0,1	0,3	0,29	1	0,19	0,01	0,04	0,06	0,02	0	0	0	0	0,02	0,01	0,01	0	0,05	0,01
8	0,04	0,05	0,22	0,14	0,4	0,51	0,25	1	0,25	0,21	0,19	0,05	0,28	0,28	0,17	0,18	0,01	0,18	0,08	0,48	0,22	0,12
9	0,17	0,25	0,34	0,16	0,31	0,13	0,05	0,19	1	0,7	0,68	0,46	0,26	0,56	0,1	0,42	0,13	0,16	0,09	0,45	0,3	0,17
10	0,13	0,15	0,23	0,11	0,27	0,18	0,07	0,23	0,46	1	0,6	0,38	0,17	0,51	0,06	0,22	0,04	0,09	0,04	0,28	0,16	0,04
11	0,09	0,15	0,19	0,12	0,2	0,21	0,07	0,24	0,3	0,38	1	0,34	0,12	0,34	0,05	0,44	0,08	0,16	0,07	0,23	0,21	0,14
12	0,17	0,25	0,22	0,11	0,25	0,14	0,06	0,11	0,41	0,4	0,21	1	0,18	0,66	0,04	0,65	0,11	0,12	0,14	0,13	0,18	0,12
13	0,31	0,28	0,44	0,21	0,19	0,14	0	0,14	0,23	0,26	0,19	0,15	1	0,38	0,44	0,24	0,23	0,23	0,15	0,31	0,15	0,09
14	0,14	0,11	0,19	0,1	0,21	0,13	0	0,13	0,35	0,42	0,26	0,4	0,32	1	0,24	0,53	0,16	0,14	0,15	0,33	0,15	0,08
15	0,18	0,13	0,27	0,12	0,13	0,14	0	0,11	0,15	0,14	0,12	0,09	0,46	0,2	1	0,56	0,62	0,33	0,43	0,3	0,1	0,03
16	0,04	0,07	0,04	0,08	0,14	0,05	0	0,06	0,25	0,26	0,26	0,37	0,13	0,34	0,23	1	0,42	0,24	0,38	0,35	0,22	0,13
17	0,17	0,1	0,11	0,05	0,12	0,04	0,07	0,02	0,2	0,09	0,09	0,14	0,18	0,12	0,36	0,18	1	0,3	0,36	0,17	0,05	0,02
18	0,17	0,23	0,2	0,09	0,2	0,14	0,07	0,11	0,27	0,2	0,12	0,21	0,11	0,1	0,29	0,16	0,18	1	0,13	0,33	0,13	0,09
19	0,08	0,09	0,09	0,11	0,17	0,14	0,04	0,1	0,19	0,16	0,12	0,2	0,16	0,13	0,27	0,28	0,25	0,3	1	0,14	0,2	0,04
20	0,05	0,08	0,18	0,19	0,2	0,14	0,04	0,16	0,28	0,32	0,21	0,18	0,19	0,16	0,23	0,2	0,15	0,31	0,27	1	0,27	0,16
21	0,05	0,16	0,09	0,06	0,19	0,14	0,1	0,19	0,25	0,19	0,19	0,26	0,11	0,16	0,1	0,25	0,17	0,17	0,28	0,21	1	0,46
22	0	0,11	0,05	0,1	0,26	0,11	0,04	0,13	0,17	0,09	0,06	0,18	0,07	0,1	0,04	0,08	0,07	0,19	0,12	0,15	0,25	1

We will also consider the relationship between topics 15 (Mechanical waves) and 17 (Optics). Let's list the connectivity indicators: vacuum, wave, diffraction, length, interference, maximum, period, surface, transverse, longitudinal, velocity, the difference in the waves course, spherical, sine, phase, velocity ~ momentum, velocity ~ kinetic, wave ~ oscillations, period ~ frequency, energy ~ intensity (Similarity (T_{15}, T_{17}) = 0.49). The connection between topics 10 (Laws of direct current) and 11 (Current in various media) is expressed in the use of the concepts: charge, voltage, electric field strength, constant, potential, work, current strength, speed, resistance, current, specific, electric, electron, charge ~ current, electron ~ electric, electric ~ charge, power ~ work, voltage ~ electric field strength, work ~ energy, emf ~ voltage, electric ~ electrolyte, electric ~ electrolysis (Similarity(T_{10},T_{11}) = 0.49).

As can be seen from Table 1, the vast majority of topics are related to each other, but some connections are weak. Based on the found values of Similarity(T_A,T_B), an oriented graph of semantic connections of the school physics course is constructed (Fig. 1.1). Its vertices correspond to the 22 topics listed above, and the edges correspond to the connections between them with an average bond strength of Similarity(T_A,T_B) $\geq$ 0.3. For $i < j$, the edge is directed from T_i to T_j. Strong bonds, for which Similarity(T_A,T_B) $\geq$ 0.5, are marked with square labels. It can be seen that the themes 5, 8, 9, 12, 13, 15, 18, 19, 20, 21 are poorly related to previous topics (for them, Similarity(T_A,T_B) is less than the threshold value of 0.3). That is, the student, having finished studying statics (topic 4, the last in mechanics), proceeds to the basics of molecular kinetic theory (topic 5), which is loosely related to topic 4. After studying topic 8 (thermodynamics), the student begins to master electrostatics (topic 9). It is clear that such "cognitive leaps" cannot be avoided, but we can try to take them into account.

A strong relationship (Similarity(A, B) $\geq$ 0.5) is found between the topics: 3 – 13, 5 – 8, 9 – 10, 12 – 14, 12 – 16. So before studying the 14th topic (Electromagnetic vibrations) and the 16th topic (Electromagnetic waves), it is necessary to master the topic well 12 (The magnetic field. Electromagnetic induction). The most important topics for understanding the subsequent training material are: 3 (6 outgoing connections), 9, 10, 15 (4 outgoing connections each). Subject 7, 11, 17, 18, 22 (the last one) either have no outgoing connections, or they are weak (less than 0.3).

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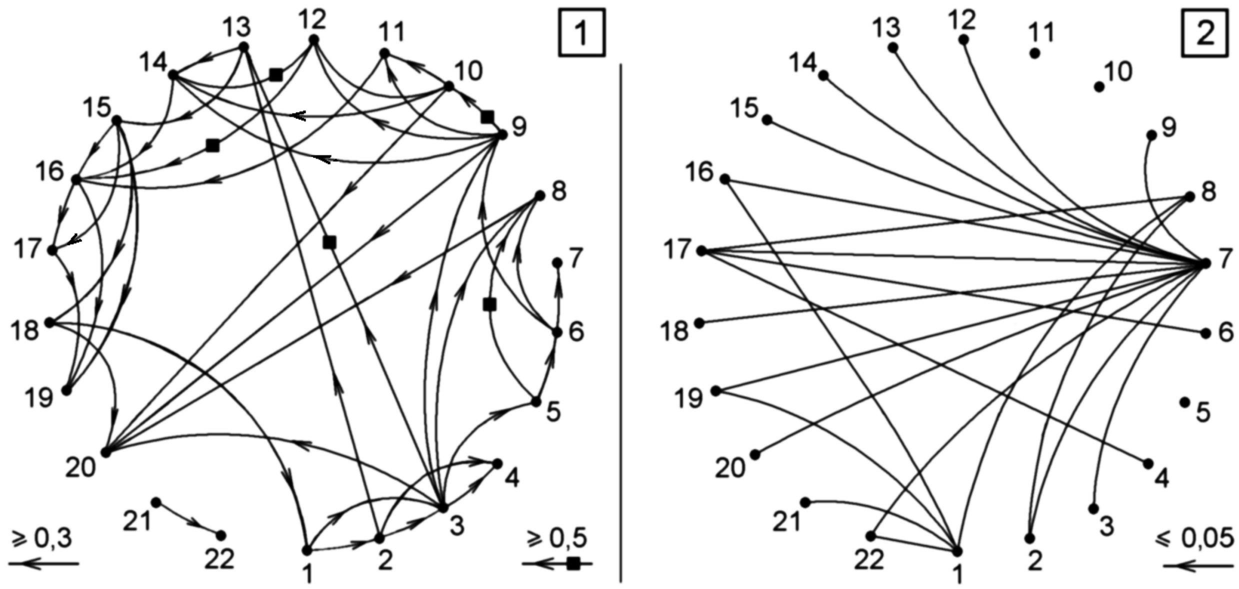

Fig. 1. Connections between the topics of the school physics course.

Figure 1.2 shows an "inverted" graph showing weak or missing connections for which Similarity(A, B) is in the range [0; 0.05[. It can be seen that topic 7 (Solids, liquids and gases) is loosely related to 12 other topics; the degree of its integration in the physics course is minimal. The weak connection or its complete absence between topic 1 and topics 8, 16, 19, 21 and 22 is explained by the fact that the concepts of kinematics are not used in the study of thermodynamics, the electromagnetic waves theory, the radiation and spectra theory, and the microcosm physics. Topic 17 (Optics) is loosely related to topics 4, 6 and 8 (Statics, Molecular kinetic theory, Thermodynamics). For all other connections not shown in the graphs (Figures 1.1 and 1.2), Similarity(T_A, T_B) lies in the range [0.05; 0.3[.

Conclusions

The intrasubject connections of the physics course contribute to the formation of knowledge about natural phenomena among students. The article proposes an objective method for identifying semantic links between various topics of the school physics course. It consists in writing out key concepts for each topic and determining their frequencies, which play the role of semantic coordinates. Using a computer program, the degree of semantic proximity of two topics is calculated as the cosine of the angle between the vectors and using the Dice formula. As result, the matrix of proximity indicators for 22 topics is obtained, on the basis of which an oriented graph is built. Its vertices correspond to themes, and its edges correspond to connections. It is an approximate model of the school physics course that helps to identify the most important topics, which are associated with a large number of other topics, and topics with a small number of incoming and outgoing connections. All this makes it possible to assess the connectivity degree of the school physics course and can be taken into account when further improving teaching methods. The proposed method can be used to identify intra- and interdisciplinary connections of other disciplines (mathematics, chemistry, biology, geography, etc.).

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