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Physics textbooks and its network structures

Petra Kralikova*, Constantine the Philosopher University, Nitra, Slovakia
Aba Teleki, Constantine the Philosopher University, Nitra, Slovakia

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Abstract

We can observe self-organised networks all around us. These networks are, in general, scale-invariant networks described by the Barabasi-Albert model. The self-organised networks show certain universalities. These networks, in simplified models, have scale-invariant distribution (power law distribution) and the characteristic parameter α of the distribution has value between 2 and 5. Textbooks are an essential part of the learning process; therefore, we analysed the curriculum in secondary school textbooks of physics from the viewpoint of semantic network structures. We converted the textbook into a tripartite network, where the nodes represented sentences, terms and formulae. We found the same distribution as for self-organised networks. Cluster analysis was applied on the resulting network and we found individual modules—clusters. We obtained nine clusters, three of which were significantly larger. These clusters presented kinematics of point mass, dynamics of point mass and gravitational field with electric field.

Keywords: Physics textbook, scale-invariant distribution, semantic network.

* ADDRESS FOR CORRESPONDENCE: **Petra Kralikova**, Constantine the Philosopher University, Nitra, Slovakia
E-mail address: petra.kralikova@ukf.sk

1. Introduction

Pupils and students often encounter written text in the learning process. Written text plays an important role in the development of the student, whether to form a personality or to acquire new knowledge. The textbooks are an essential part of acquiring knowledge, so the textbooks should be written in a comprehensible way. In our work, we focus on the curriculum of physics textbooks in terms of the structure of the semantic network. Textbooks for each year should build on themselves, and textbooks from related subjects should complement each other. We analyse textbooks by network tools at the level of microstructure. The curriculum microstructure is not a division into individual chapters, subchapters, states, but the whole content of the interpretation, i.e., sentences, including pictures, tables, tasks, examples, formulae, etc.

Networks that make up the various network structures consist of nodes (vertices) that are joined by links (edges). The networks are described by various properties such as, number of nodes (N), number of links (k), average number of links ($<K>$), networks diameter (d), average path length ($<d>$), modularity, robustness, shortest path and many others (Barabasi, 2014). Using modularity or clustering, the network can be divided into smaller parts—modules or clusters that consist of strongly interconnected nodes. These nodes of the same cluster are closer to one another than to nodes of other clusters.

Networks are all around us, for example, a topological map of the Internet, web, proteins and relationships between individuals. The first model for networking was studied by Erdosi and Renyi, who says that random networks are created with the Poisson distribution. It turns out that this model is not suitable for real networks. Barabási described the universality of network topology and showed that the networks created by natural evolution are independent of their age, function or scale and have similar structures (Barabasi, 2009). In many cases, real networks follow scale-invariant (power) distribution (Albert, Jeong & Barabasi, 2000; Barabasi, 1999; 2009; Jeong, Tombor, Albert, Oltvai & Barabasi, 2000). The probability of a scale-invariant network is proportional to

$$p_k \propto k^{-\alpha}$$

where *p(k)* is the probability that a node has *k* links. The analysis made by Barabasi (1999) shown that the self-organising networks have its parameter α between 2 and 5. We found that the same is true for the investigated physics textbooks too.

2. Methodology

We chose physics textbook Fyzika pre 1. rocnik gymnazia [Physics for the 1st year of high school] (Vachek, Bednarik, Klobusinsky, Marsak & Novak, 1984), which deals with the themes of Mechanics, Gravitational field and Electric field—the textbook is divided into eight chapters and represents 255 page-long educational text. We transformed the text into a network consisting of three types of nodes, to a tripartite network (with three types of nodes: sentences, terms and formulae). Before we performed the detailed analysis, we defined what we consider to be nodes of these types.

For nodes representing sentence type nodes, we have included sentences, images, tables, notes, tasks and examples—for more specific explanation, see our article Physics textbooks from the viewpoint of network structures (Kralikova & Teleki, 2017). The terms, the nodes of this type, are the physical concepts and names of the persons. The formula type nodes are physics formulae, equations, symbols of physical quantities and units.

We consider a word to be a physics term if it is listed in the dictionary of physics concepts (Physical dictionary Slovak-English and English-Slovak) (Cernansky et al., 2007), (Physics terminology) (Garaj et al., 1987) or in the index of the textbook (Vachek et al., 1984).

We defined when there is a connection between nodes. The sentence type node can be linked to all node types (sentence, term and formula). Term type node can only be connected to the node of sentence type if and only if the term is the part of this sentence. Similarly, formula type node is connected to the sentence type node if and only if the formula is a part of this sentence. Sentence type node is linked to sentence type node if one sentence refers to the other sentence by transitional words and transitional phrases.

We have analysed the above-mentioned textbook and processed to semantic network with three types of nodes. We have further processed the structured data using Gephi and obtained a network that can be visualised, manipulated and analysed topologically and statistically. The tools of this program allow us to provide cluster analysis of the textbook (by selecting parameters to determine the number of clusters in the network).

3. Results

We have obtained a tripartite network consisting of 4,503 nodes and 12,023 links. This network is in Figure 1, where the yellow nodes are sentences (2,901), red nodes are terms (543) and blue nodes are formulae (1,059).

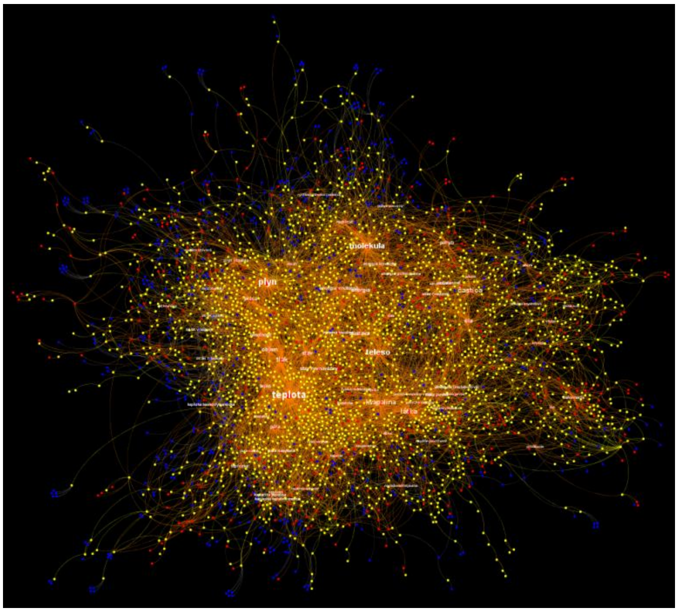

Figure 1. The tripartite network representing a textbook of physics

We constructed the histogram of the complementary function distribution. The complementary function distribution of a scale-invariant distribution has approximately in the following form

$$p_K \sim k^{-\alpha+1}$$

The histogram for the complementary function distribution is shown in Figure 2, where

$$M_j = N\sum_{i=1}^{j-1} n_i$$

and *N* is the total number of nodes (in our case *N* = 4,503) and n_i is the number of nodes with *i* links.

The fitted complementary distribution function is given by the equation, $M=M_0k^{-(\alpha+1)}=9033,26k^{-1,41}$ where α is the parameter describing the scale-invariant network. Parameter α.has a value 2.41 and this value is within the same interval as the self-organised network.

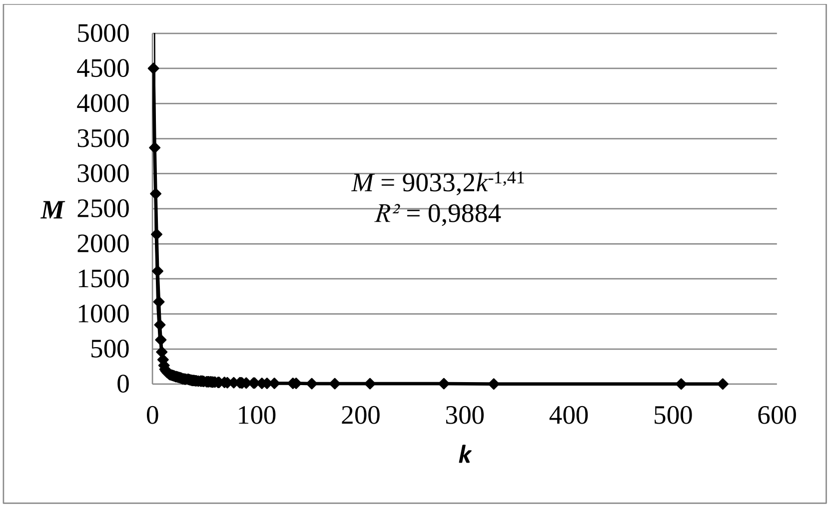

Figure 2. The histogram of the complementary distribution function of the frequency distribution of the nodes *M* depending on their degree *k*

We can see that there are many terms in the Figure 1 that have one or two links, but there are also several terms that have significantly more connections (these are special central concepts like energy, mass, etc.). This is typical for a scale-invariant network. More specifically, 1,130 nodes have one link only. From these nodes, 140 are terms (131 physical concepts and 9 personal names). The most common physical concepts in the text are: force (with 548 links), body (508), velocity (328), motion (280), field (209), mass (175), electric charger (153), point mass (138), energy (135) and liquid (117).

The main advantage of our transformation of textbooks on a tripartite network is the possibility to study didactic tasks using mathematical tools (topological tools, statistical tools, etc.). For example, using cluster analysis, we obtained nine clusters, which we can see in the Figure 3. We paid attention to the three largest clusters (resolved by yellow, violet and green colours in the Figure 3). We emphasise that the clusters obtained were the result of a topological analysis.

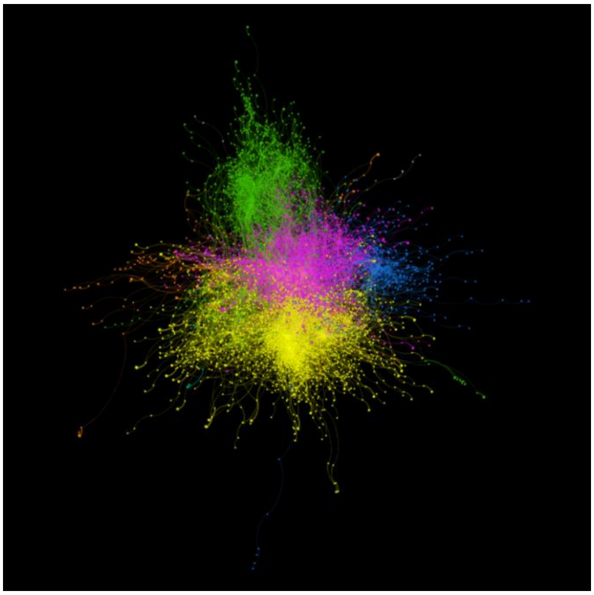

Figure 3. Semantic network divided into 13 clusters

The largest cluster is shown in Figure 4. This cluster contains 1,790 nodes and 3,998 edges and has scale-invariant distribution with parameter α = 2.427. The value of this parameter falls within the range as shown by the self-organised networks. The number of nodes with one link was 506. From these nodes, 27 are terms (27 physical concepts). Physics terms most frequently occurring in the text are: velocity (328), motion (280), point mass (138), displacement (105), uniform motion (90), trajectory (97), time (78), acceleration (85), momentum (84) and reference frame (69). These terms are conceptual for mechanics, more precisely kinematics.

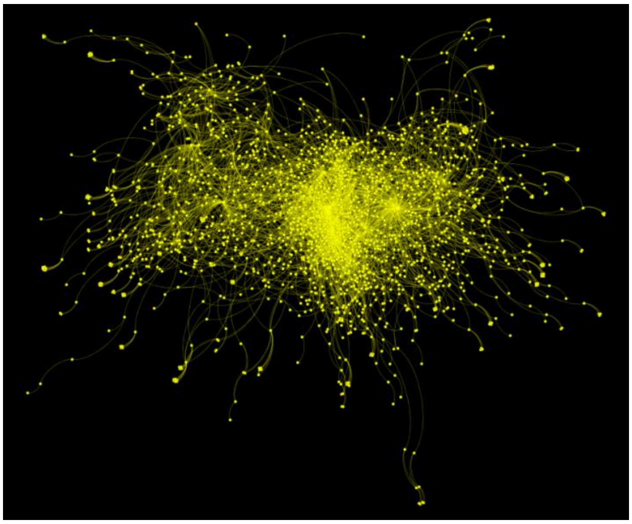

Figure 4. The largest cluster obtained by cluster analysis of the resulting semantic network

The second largest cluster is shown in Figure 5—includes 1,180 nodes and 2,796 links and has scale-invariant distribution with parameter α = 2.350. There are many nodes (273) with one connection at the boundary of this network. From these nodes, 25 are terms (23 physical concepts and 2 personal names). Physics concepts most frequently occurring in the text are: force (348), body (306), energy

(135), mass (175), work (110), weight force (63), position (72), potential energy (48), action (42) and equilibrium position (32). These terms are conceptual for mechanics, more precisely dynamics.

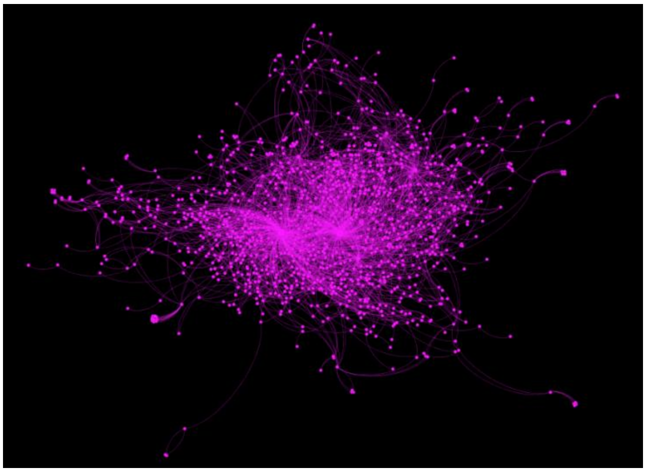

Figure 5. The second largest cluster obtained by cluster analysis of the resulting semantic network

The third largest cluster is shown in Figure 6—includes 987 nodes and 2,386 links and has scale-invariant distribution with parameter α = 2.413. The number of nodes with one link was 237. From these nodes, there were 52 terms (50 physical concepts and 2 personal names). Physics concepts most frequently occurring in the text are: field (190), charge (143), gravitational field (92), electric field (81), electric charge (63), potential (54), field intensity (52), conductor (48), distance (40) and capacitor (36). This cluster is focused on gravitational and electric field.

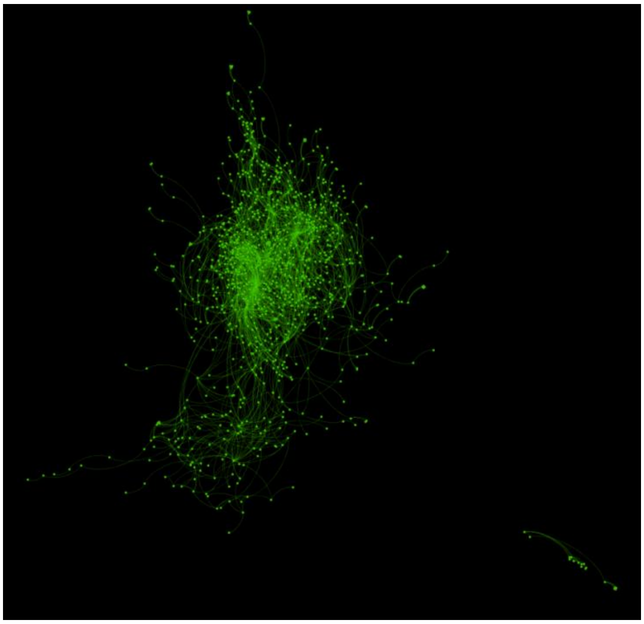

Figure 6. The third largest cluster obtained by cluster analysis of the resulting semantic network

Despite the fact that the cluster analysis parameters were elected to find three clusters, the remaining text formed six isolated clusters (see Figure 7) and contained 546 nodes and 803 links, representing 12.13% of total network structure (textbook). Nodes with one link were up to 186, representing in particular formulae.

Physics concepts occurring most frequently in the text are: liquid (82 links), physics (35), pressure (31), flow (26), ideal liquid (13), streamline (11), gas (10), pressure energy (9), measuring unit (9) and manometry tube (9).

Figure 7. Remaining clusters obtained by cluster analysis of the resulting semantic network

The basic properties of the resulting network and clusters are summarised in Table 1.

Table 1. Network properties and individual clusters

	N	*k*	N_1	N_2	N_3	<*k*>	*d*	<*d*>	*α*
Resulting network	4,503	12,023	2,901	543	1,059	5.341	14	4.584	2.410
Yellow cluster	1,790	3,998	1,130	135	525	4.467	13	4.669	2.427
Purple cluster	1,180	2,796	793	122	265	4.739	9	3.782	2.350
Green cluster	987	2,386	636	172	179	2.417	13	4.376	2.413
Cluster 4–9	546	803	343	114	89	1.471	20	6.381	2.622

Where *N*—number of nodes, *k*—number of links, N_1—number sentences, N_2—number terms, N_3—number of formulae, <*k*>—average number of links, *d*—diameter, <*d*>—average length and *α* —parameter describing the network.

4. Discussion

Using network and cluster analysis of the tripartite network, we have achieved interesting results. The scale-invariant distribution occurs in all clusters. Each network has many nodes with one link at its boundary. This is typical for a scale-invariant distribution. Ideally, term-type nodes should not have only one link, as the term acquires its meaning in context and is better understood if it occurs in several contexts. In the resulting network, there were 146 term-type nodes that had one link. Using Gephi, we performed a cluster analysis and found nine clusters despite the fact that the analysis parameters were selected to find three clusters. Of course, three of nine clusters were robust. We focused on the three largest clusters which together represented 87.87% of the entire semantic tripartite network (the textbook). The basic characteristics of these networks are shown in Table 1.

The two largest clusters are a part of a physics textbook that focuses on mechanics. The first cluster focuses on point particle kinematics and the second cluster focuses on point particle dynamics. The third largest cluster focuses on gravitational and electric fields. The remaining clusters represent 12.13% of the entire network. The largest of them, cluster 4, is focused on fluid and gas mechanics. The cluster 5 has devoted a portion of the resulting network that focuses on quantities and units used in physics. Clusters 6, 8 and 9 are examples, especially the formulae. Cluster 7 is a historical note mostly by personal names.

5. Conclusion

Physical textbooks play an important role in educational processes, and they translate the curriculum into a detailed semantic structure. In this way, they represent a topological network that can be analysed by topological analysis tools. In our work, we described the resulting transformation of the textbook of physics for the first year of the secondary school into a tripartite semantic network. Through topological analysis, we can find out many properties of semantic networks, not only the properties listed in our article (the basic properties are shown in Table 1). In our opinion, almost all, if not all, questions and tasks of didactics can be presented as a topological characteristic, characteristic or process on a topological structure. From our analysis, we can see one shortcoming of our textbook. There are many nodes with a single link and many of them are term nodes (mostly concepts of physics and personal names). We can say that the network properties of the analysed part correspond to the criteria of self-organised networks although there is a high occurrence of one-time terms. The presented method of analysis also provides the opportunity to analyse the interconnection of physics textbooks for various years of study and the interconnection of physics textbooks and related disciplines (mathematics, chemistry, biology and geography). The number of usable tools from network analysis increases with the growth of the processed part of the textbooks.

Acknowledgements

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