Using the Concept Map Technique in Teaching Introductory Cell Biology to College Freshmen

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Abstract: In our study, we focused on the conceptual understanding of the concepts and processes presented in the first lectures of an introductory course in cellular biology for biology majors. The study topic we considered was, "the structure of DNA and the functions of nucleotides". One hundred and eighteen students were asked to prepare concept maps from a list of twenty given concepts. Analysis of these maps has shown a compartmentalization into two major groups of concepts. The most frequent concepts were from the genetic aspect, while frequencies of concepts from the energetic aspect were comparatively low. Many students did not recognize that molecules like ATP or GTP are simply nucleotides. Other interesting misconceptions concerned the concepts of nucleic acids, purines and pyrimidines. One of the advantages of using the concept map technique was that it encouraged the instructor to start using maps as a graphic instructional tool, summarizing his lectures. In addition, the need to select twenty concepts and arrange them in a map forced him to go over his lectures and reconsider whether or not these concepts should have been selected for instruction.
Key words: conceptions, concept map, undergraduate, genetic material, energy balance, cell biology,

INTRODUCTION

This paper describes a case study that aims to explore students' understanding of concepts and processes in an introductory cell biology course, at the Life Sciences Department, Tel-Aviv University. We started this study due to two main reasons.

One reason was students' statements, such as: "…This course [introductory cell biology], sometimes feels like a shower of new concepts threatening to drown me out. It seems that I have a thousand new words in my head and I can't draw the whole picture", or "There are many different words alike: amino acid, nucleic acid, nucleotides, nucleosides… and I can't arrange them in my mind…" Since all of the course lectures were videotaped, we carefully observed the first six lectures of the course. What was immediately apparent from the videotapes was the large number of concepts (sometimes over 50) that the instructor mentioned in each lesson. Moreover, most of these concepts are on the molecular level, and to many students, who did not study either advanced biology (40% of freshmen) or chemistry (56% of freshmen) in high school, these concepts are completely new.

The second reason for this study was the course instructor's wish to explore students' understanding of concepts and processes, since in previous years students tended to describe this course as challenging and interesting, but very difficult in terms of subject matter. This instructor later became an active partner (third author) in our research. It is also worth mentioning that the "cell biology" course is one of the corner stones for life sciences majors in their first year of their undergraduate studies.

We believe that students' experience in the first year of their studies is a very important element in their decision to stay or leave their field of study. Tobias (1990) claims that introductory science courses are responsible for driving away many students who started off majoring in sciences programs. One of the negative features of these courses, Tobias mentioned, is that they do not pay enough attention to students' conceptual understanding. Trowbridge and Wandersee (1996) stressed that in introductory science courses it is especially important for instructors to be aware of students' understanding, since these courses bring into play "large conceptual frameworks" (Trowbridge & Wandersee, 1996, p.54).

Thus we decided to focus on the first lectures of the introductory cell biology course and to try to reveal students' conceptual understanding. The subject we focused on was, "the structure of DNA and the functions of nucleotides." We chose this subject, since understanding the molecular structure of DNA is an important goal in teaching biology, especially in our era (Wilcoxson, et al., 1999), which includes the human genome project and gene therapy. However, molecular biology, with its heavy emphasis on minute details and abstract concepts, is considered to be an intellectual challenge that many sophomores are not developmentally ready to engage (Malacinski & Zell, 1996).

In the last two decades there has been much interest in investigating students' conceptions concerning DNA (Bahar, et al., 1999; Garton, 1992; Hallden, 1988; Johnstone & Mahmoud, 1980; Marbach-Ad, 2001). Most of these studies focused on students' understanding of the functions of DNA as the genetic material (Bahar et al., 1999; Fisher, 1983; Kindfield, 1994; Lewis, 1996; Malacinski & Zell, 1996; Marbach-Ad, 2001; McInerney, 1996), and more specifically understanding the concepts of DNA, RNA, gene, chromosome (Lewis & Wood-Robinson, 2000), and protein, and the processes of DNA replication, transcription and translation. Studies of various age groups, ranging from high school students (15-17 years) to university professors of genetics examined their understanding of basic molecular biology processes (Hildebrand, 1986 and 1991; Kindfield 1992). The research compared novices and experts concerning their conceptions and ways of dealing with genetic problem solving. Kindfield states that "some of the most crucial processes are consistently cited as the most difficult components of biology to learn." Similarly, Fisher (1983) reported that college students in an upper-division introductory genetics course for science majors had difficulty identifying the products of translation given the following multiple choice options: a) amino acids, b) transfer RNA, c) activating enzymes and d) messenger RNA. Many (45%) failed to identify the correct molecules as "c) activating enzymes".

In contrast to the rich literature about the functions of DNA, students' conceptions concerning the functions and the structure of the nucleotides (DNA's building blocks) have been rather neglected, even though they take a central part in cellular processes. The nucleotides are involved in both the genetic aspect of the living cell, as well as in its energetic aspect (e.g., ATP, GTP) - playing a major role in regulating cell reactions.

The desire to explore students' understanding of a certain subject or concept is shared by psychologists (e.g., David Ausubel), science educators (e.g., Joseph Novak) and philosophers (e.g., Bob Gowin). Novak and Gowin developed the concept map technique as a way of capturing participants' understanding of the portal concept (Novak & Gowin, 1984). Concept mapping is a technique for externalizing concepts and propositions that express the relationships between concepts. This method was originally used as a way of "determining how changes in conceptual understanding were occurring in the students" (Novak, 1990, p. 937).

Maps have a long and noble intellectual history. Concept maps were originally intended as graphic organizers to be constructed by the specialist - not by the learner -and they consisted of boxed concepts connected by unlabeled lines, so the exact nature of the relationship between them remained unspecified for the learner (Trowbridge & Wandersee, 1998).

There is a great variety of graphic organizers, including flowchart, roundhouse diagram, and vee diagram used in teaching today (Trowbridge & Wandersee, 1998), as a diagnostic tool, as an instructional tool and for assessment and evaluation. Recently, Bahar et al. (1999, p.134), for example, used a word-association test to map the cognitive structure of areas of elementary genetics in first-year biology students. The underlying assumption in a word-association test is that the order of the response and retrieval from long-term memory reflects at least a significant part of the structure within and between concepts (Shavelson, 1972). The results of Bahar et al.'s study showed that the students generated many ideas related to ten key words, but they did not see the overall picture as a network of related ideas.

In our study we decided to use the concept map technique, but not in the classic way characterized by Novak and Gowin (1984). Thus, students were not initially trained to draw maps due to the time limitations imposed by the course. Instead, we explained the basic principles of concept maps, showed examples of concept maps in various topics (Novak & Gowin, 1984), stressed the importance of drawing as many lines as possible between the twenty concepts with which the participants were presented, and of writing a proposition for each line.

METHODS

Course description

The introductory cell biology course for freshmen at Tel-Aviv University is a four-credit, one semester class (28 lectures - two hours, twice a week). Three instructors from the department of cell research and immunology teach the course in rotation, each of them specializing in specific topics. The instructors cooperate and build the curriculum as a successive unit. The course rationale is to teach the central cellular processes from both a functional and a structural viewpoint, emphasizing basic cellular mechanisms, while paying relatively less attention to cell morphology. The six first lectures serve as an introductory chapter to the course, providing a systematic overview of the macromolecules (carbohydrates, phospholipids, nucleic acids, and proteins) that build the cell and are involved in the life cycle processes. The instructor emphasizes similarities in macromolecular structures by presenting each one of them, except phospholipids, as a polymer chain, consisting of monomer building blocks.

After these first six lectures, when the students are aware of the basic components of the cell, the next chapter (six lectures) begins with processes that take place in the nucleus (e.g., DNA replication, transcription, chromatin division). Another chapter (six lectures) deals with specific topics such as protein transport, the cytoskeleton and the process of endocytosis. The next three lectures deal with specific organelles, such as endoplasmic reticulum, lysosome and mitochondrion. The final three lectures are dedicated to generic aspects, such as differentiation, cancer, viruses and cell cycle regulation.

The recommended textbooks are: *Molecular Biology of the Cell* (Alberts, et al., 2002) and *Essential Cell Biology* (Alberts, et al., 1998). It is suggested that students read 2-3 pages from the textbooks for each lecture. The reading is optional, and the specific subjects that are covered in the reading task are not discussed in class, but account for 10% of the final exam score. Since the lectures are in Hebrew and the textbooks are in English, students learn primarily from their lecture notes, instructors' videotapes, and Power Point presentations. The Power Point presentations used by the instructors in class present artwork from the textbook, in order, to increase students' familiarity with the textbooks and, to bridge between the Hebrew lectures and the English textbooks. Thus, the graphics are presented in English, while the lectures are in Hebrew. The instructors' Power Point presentations are made available to students.

Eleven discussion sessions accompany the lectures and are conducted by teaching assistants (TA). They are designed to allow students to practice and expand their knowledge. Though sessions are optional**,** most students attend them.

Overview of the present study

The study was conducted in the spring of 2002. Over four hundred biology majors (463) were enrolled in this class and were arbitrarily divided into two classes of approximately 230 students each. These classes were taught in a traditional lecture format. The two class sessions that this study focused on were dedicated to DNA and RNA as polymers, as well as to their corresponding monomers, the nucleotides. The instructor emphasized the structure of nucleotides and their dual role as mediators of genetic information while also constituting the "currency" of energy in the cell.

During the following discussion session, a group of students (approximately 150), which were selected arbitrarily, were asked to prepare concept maps referring to twenty concepts: DNA, RNA, nucleic acids, nucleotides, ATP, dATP, ADP, GTP, ribose, deoxy ribose, sugar, phosphate, nitrogen bases, purines, pyrimidines, protein, amino acids, energy balance, monomer, and polymer.

We introduced the main features and principles of concept mapping. In addition, we exposed the students to two concept maps, taken from Novak and Gowin's classic book "*Learning How to Learn*" (1984, p.18). These two concept maps included the same concepts but constituted different structures. By introducing these maps we intended to convey that from the same concepts a number of different maps could be constructed, all of them correct as long as they represented the correct relationships among concepts. In addition, we asked the students to try drawing as many lines as they could between the twenty given concepts, and to make sure they wrote a proposition for each line.

Concept-map analysis

One hundred and eighteen concept maps were collected and analyzed both qualitatively and quantitatively. First, we examined the frequency of each of the twenty concepts in the concept maps. Then we analyzed all the propositions regarding each concept. This research did not consider whether the propositions were correct or incorrect; our main purpose was to find out if there were propositions that were shared by many students, thus reflecting alternative conceptions.

In order to analyze and characterize students' propositions, we condensed all propositions concerning each concept, or group of concepts, in separate tables. Identical or similar propositions were combined, yielding subcategories. Then, subcategories with similar ideas were combined to form major categories of "conceptions." Finally, we were able to characterize a few major categories for each concept and the frequency for each category was calculated in order to trace common conceptions.

Two other aspects examined were the structure and the scientific accuracy of the concept maps. In order to evaluate propositions, we referred to two sources: definitions from the scientific literature (Alberts, et al., 2002 & Suzuki, et al., 1999), and a map, which was constructed by Prof. Gershoni (one of the course instructors) and his TA (Figure 1).

In order to validate the categorization of the propositions, a sample of the students' maps was given to a researcher in science education, who was not connected to this study, and to a high school biology teacher. Each analysed and defined categories of propositions independently, and their categories were similar to ours.

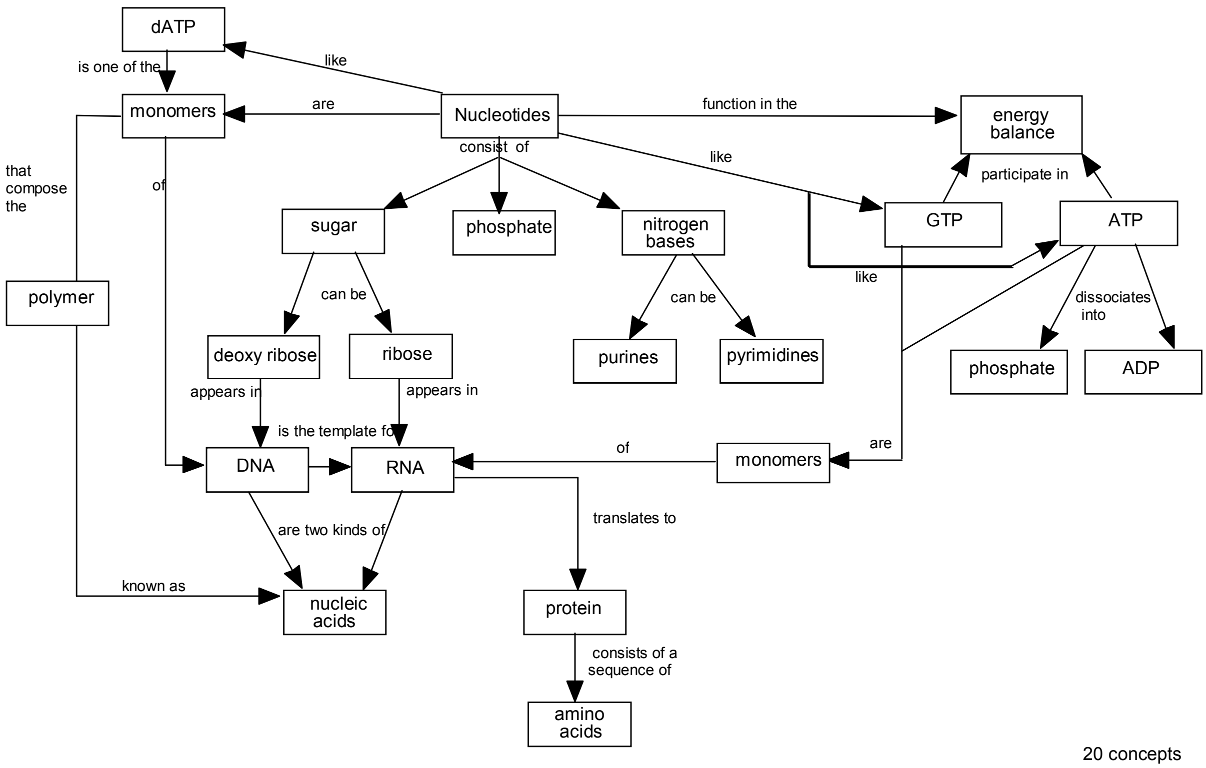

***Figure 1**. The map that the course instructor and his TA constructed from the twenty concepts*

RESULTS

Concepts and propositions in the concept maps

While analyzing students' concept maps, we first examined frequencies of each concept in students' maps and distinguished between valid and false propositions, concerning each concept (Table 1).

In Table 1 the concepts were arranged in descending order, based on their frequencies. Inspection of this table shows a compartmentalization into two groups of concepts. The most frequent concepts were: DNA (98%), nucleotides (94%), RNA (92%) and protein (92%). These concepts are key concepts, from the **genetic aspect**, and the relations among them are known as the "central dogma" (Crick, 1966). The frequencies of the concepts that are central from the **energetic aspect** of the nucleotides: ATP, ADP, GTP and energy balance, on the other hand, were comparatively low in frequency (78%, 72%, 63% and 63% respectively), with the concepts ATP and ADP being more common than the concepts GTP and energy balance. Another noteworthy finding was that dATP, a monomer specific to DNA, was the concept with the lowest frequency (39%) in the students' maps.

Table 1 also summarizes the distribution of students' propositions for each concept. We distinguished among students who had only valid propositions, only false propositions, or a combination of valid and false propositions concerning each concept. Inspection of the data shows, that although high frequency of a concept may indicate that the students are familiar with this concept, it does not guarantee that a given student appropriately understands the meaning of this concept and its relationships to other concepts. For example, the concepts of DNA and RNA, which were mentioned by over 90% of the students, appeared with valid connections only in about half of the maps (DNA- 51%, RNA- 57%).

Students' conceptions as reflected in maps

We focused on conceptions that were shared by a considerable number of students, i.e., more than 10% of them. One of the most interesting findings concerned the **nucleotides.** The most common proposition in the category of **nucleotide functions** was "Nucleotides are the building blocks of DNA and RNA" (82% of the students referred to this function), while only about a third of the students (28%) referred to the function "Nucleotides participate in the regulation of the energy balance". It is important to emphasize that these two propositions together represent the two major functions of nucleotides taught in lectures; the so-called genetic and energetic functions (the role of nucleotides as co-factors, such as NADH) are taught in subsequent lectures. Surprisingly, only 18% of the students mentioned **both** functions.

Table 1. *Percentage of students mentioning concepts and the percentage distribution of propositions of those mentioning the concepts.*

The concept	Percentage of students mentioning concept*	Propositions (relationships between concepts)		
		All valid	Some valid and some false	All false
DNA	98	51	46	3
Nucleotides	94	45	43	12
RNA	92	57	40	3
Protein	92	82	13	5
Amino acids	86	60	27	13
Polymer	85	86	12	2
Monomer	82	76	21	3
Phosphate	82	71	13	16
Purines	81	45	7	48
Pyrimidines	81	45	7	48
Sugar	80	75	17	8
ATP	78	63	33	4
Deoxy ribose	78	77	9	14
Nitrogen bases	76	72	6	22
Ribose	75	81	10	9
Nucleic acids	73	42	21	37
ADP	72	77	16	7
Energy balance	63	67	29	4
GTP	63	62	22	16
dATP	39	28	11	61

* The total number of students who constructed concept maps = 118

Another group of interesting propositions related to the **energetic aspect**. We discovered that less than half of the students (42%) connected both ATP, ADP and GTP with “energy balance”, and 24% connected **only** the ATP with “energy balance”, i.e., they did not mark any connection between GTP or ADP and “energy balance”. A false proposition made by a considerable percentage of students (12%) was that “dATP participates in the regulation of the energy balance.” It seems that some students over-generalized and extrapolated from ATP’s function to dATP.

Other interesting misconceptions were regarding **DNA structure**. For example, concerning the concept **nucleic acids,** 14% of the students incorrectly wrote, “Nucleic acids are a type of nucleotides.” On the same issue, it was interesting to see that while 12% of the students mentioned the valid proposition, ”Nucleic acids are polymers,” 15% exposed a misconception by writing “Nucleic acids are monomers,”

Regarding the concepts of **purines** and **pyrimidines**, we learned that while 23% of the students mentioned that “Purines and pyrimidines are kinds of nitrogen bases” (valid), almost twice as many (38%) mentioned that “Purines and pyrimidines are types of nucleotides” (misconception).

Structure and scientific accuracy of the concept maps

In analyzing each concept map, we discovered that, even though the students were not trained to build classic concepts maps, three major types of maps were found:

1. **Branched** concept maps, which included many cross-links (e.g., Figures 2 and 3).
2. **Fragmented** concept maps, which were divided into separate fragments, or more precisely, into discrete sub-maps (e.g., Figure 4).
3. **Linear** concept maps (like flow charts), based on single connections between concepts (e.g., Figure 5).

Table 2 summarizes the frequencies of students’ maps in terms of their structure and their scientific accuracy. Most of the students’ concept maps were branched (83%), a considerable percentage of maps were fragmented (14%), and only some maps were linear (3%). Interestingly, half of the fragmented maps (50% of the original 14%) reflected a compartmentalization between the genetic and the energetic aspects of the nucleotides’ functions.

It is worth mentioning that even though 83% of the maps included most of the concepts and were branched, inspection of the propositions indicates that most of them (80%) were only partially correct (e.g., Figure 2). Moreover, only 17% of the maps were considered absolutely correct (e.g., Figure 3).

***Table** 2. Distribution of concept maps by structure and scientific accuracy*

Category	Types	Percentage
Structure	Branched maps	83
	Fragmented maps	14
	Linear maps	3
Scientific accuracy	Absolutely correct	17
	Partially correct	80
	Absolutely incorrect	3

*The total number of students who constructed concept maps=118

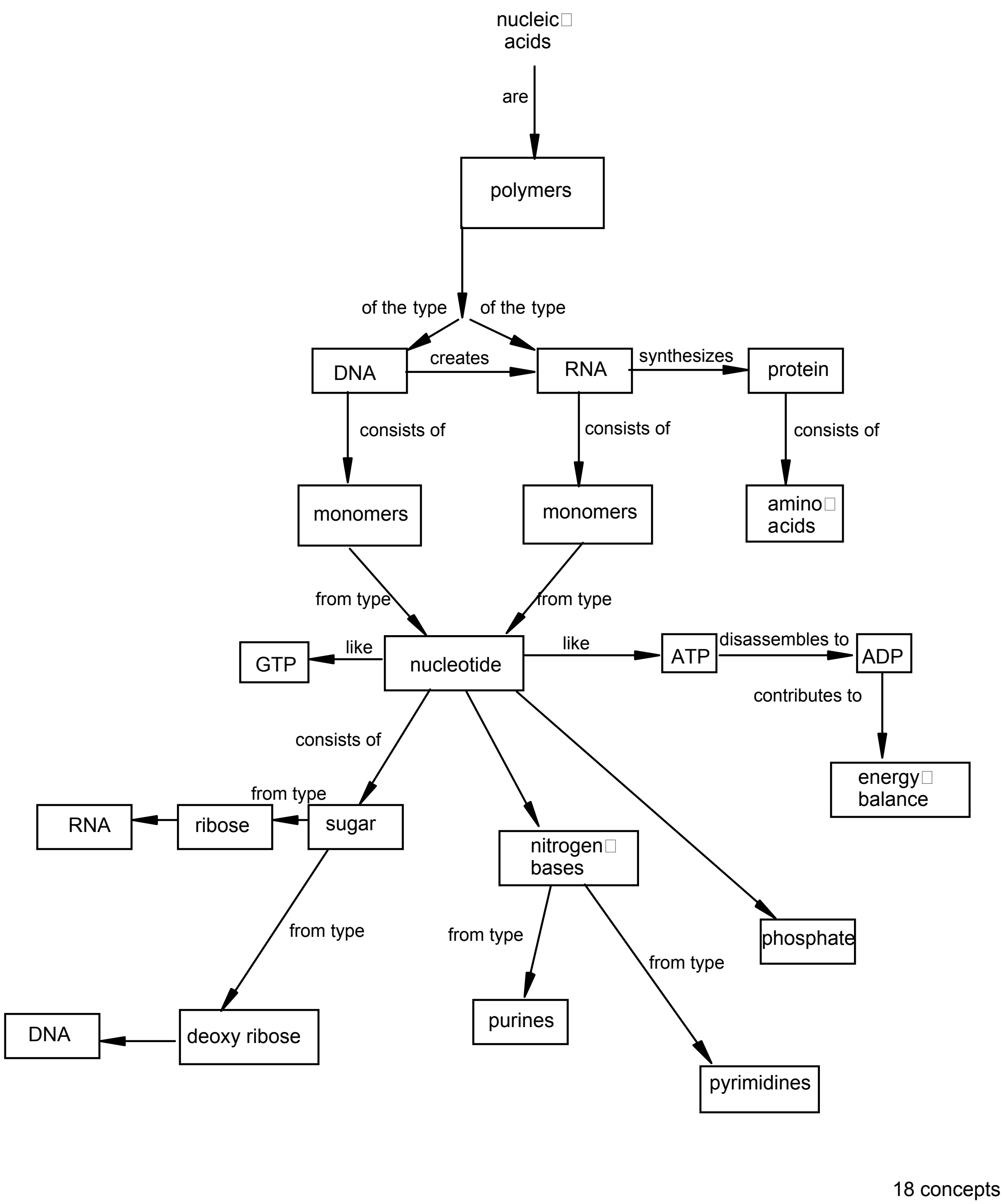

***Figure 2**. A branched concept map with only some of the propositions covered.*

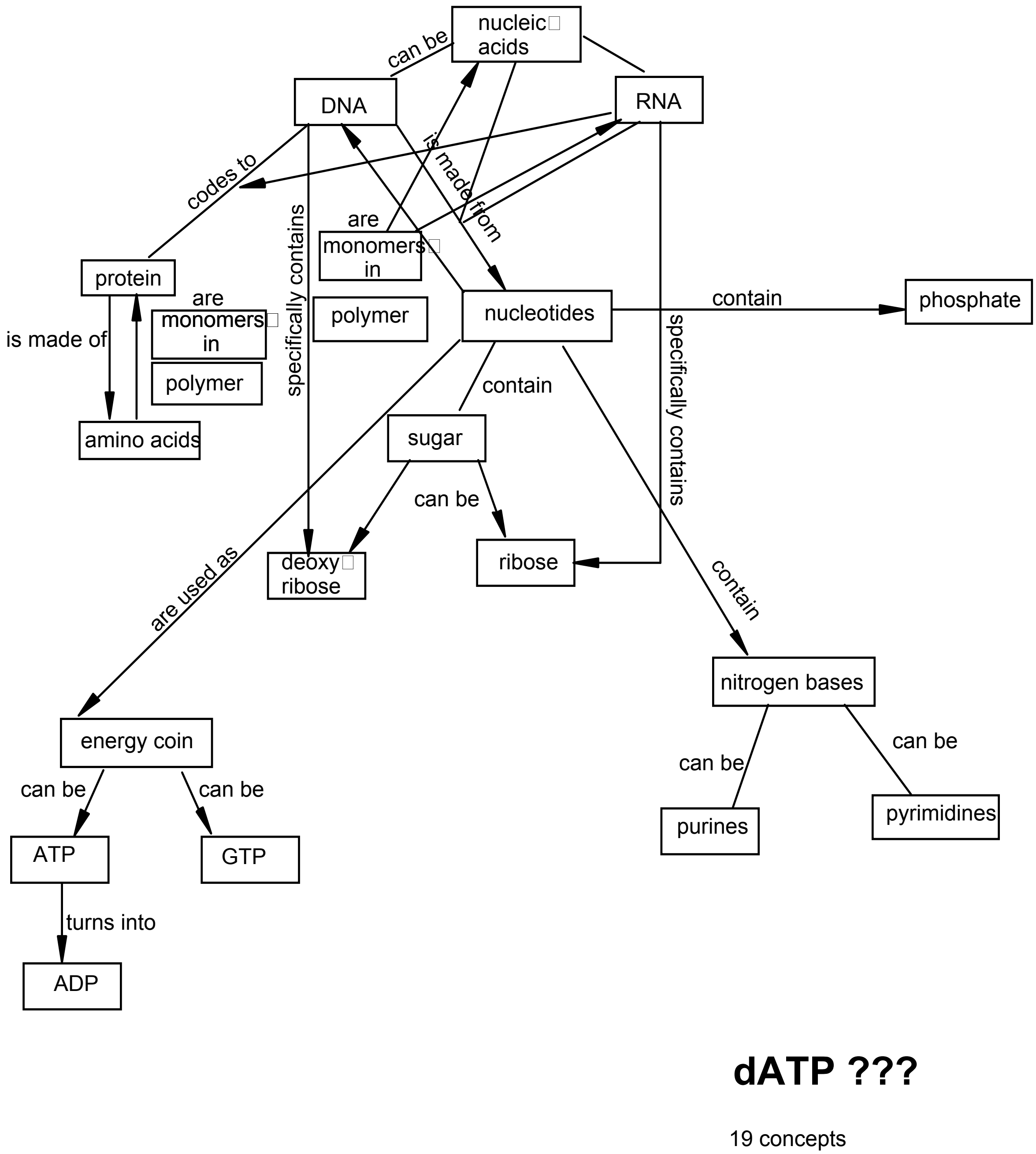

Figure 3. *A branched concept map with all propositions correct   Note: This concept map, in which all the propositions are correct, is unique*

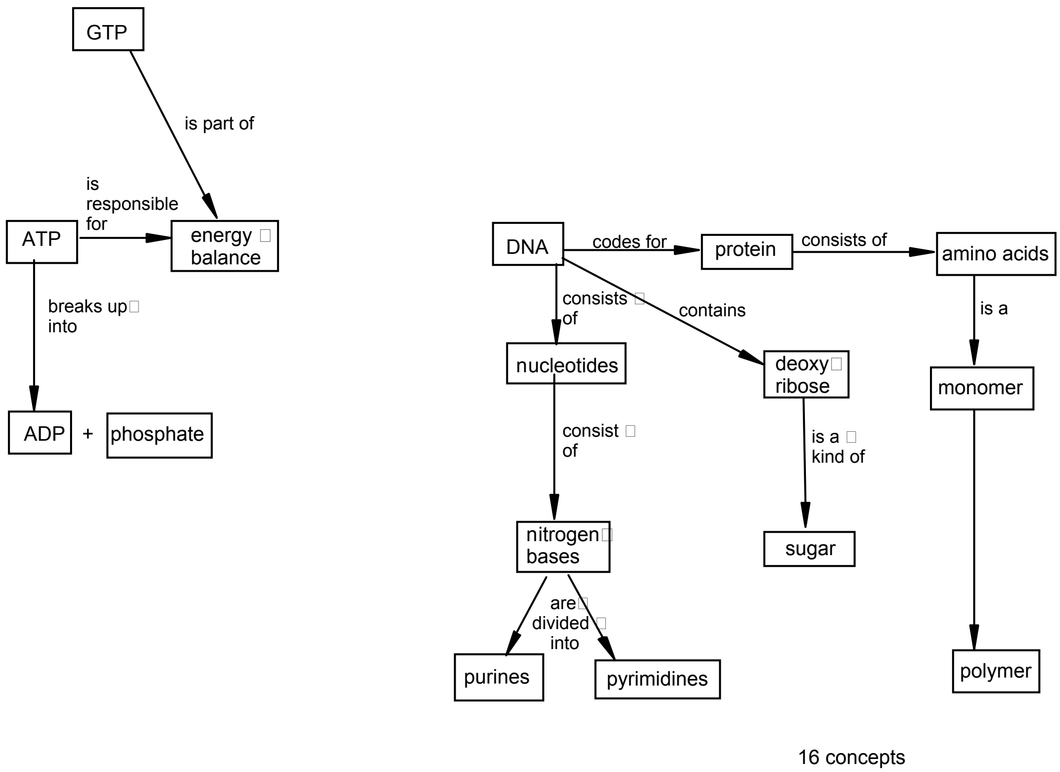

Figure 4. *A fragmented concept map. Note: This concept map represents a common compartmentalization that students made between the genetic and the energetic aspects.*

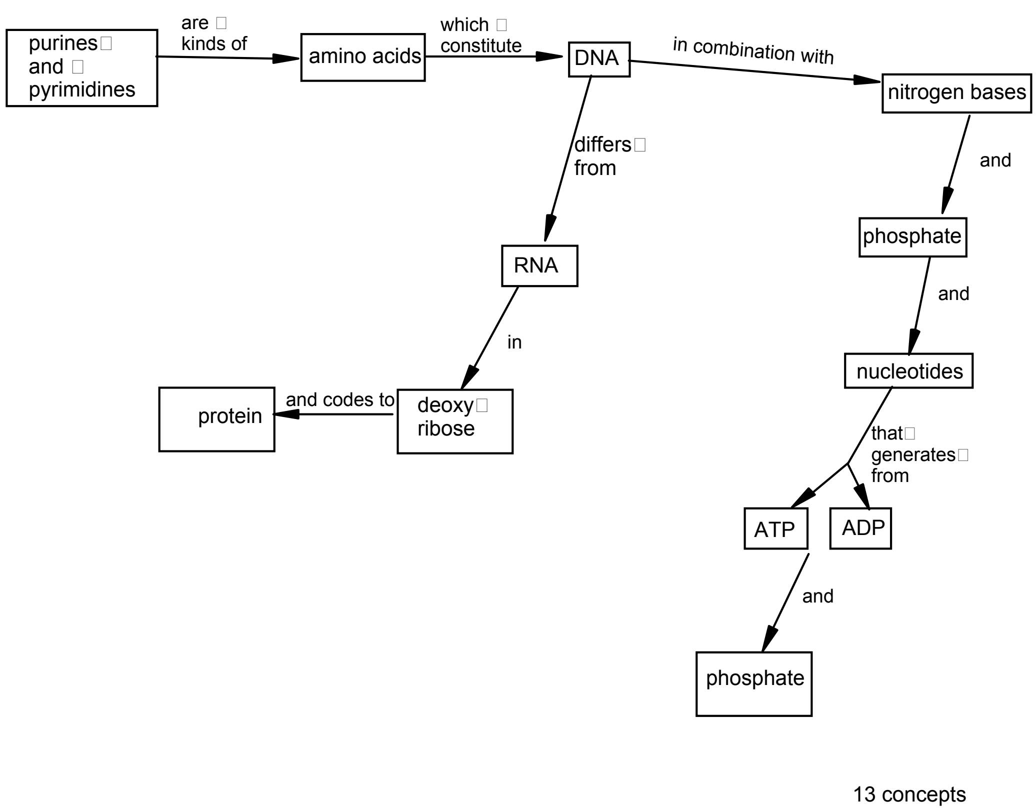

Figure 5. *A linear concept map with almost all propositions incorrect*

DISCUSSION

The aim of this study was to explore freshmen's conceptions in an introductory cell biology course, using concept map technique as a course embedded assessment tool. One of our most interesting findings in this study was students' compartmentalization between the genetic and the energetic aspects of the living cell, despite the instructor's effort to connect between them in-class. This lack of compartmentalization was especially marked in regard to the functions of nucleotides, and was observed in students' propositions as well as in the structure of a considerable number of students' maps. It seems that many students are more familiar with the genetic function of nucleotides than with the energetic one. In addition, many students did not recognize that molecules like ATP or GTP are simply nucleotides. For example, one of the students in the course said, "I learned that one of the nucleotides in the DNA is 'adenosine triphosphate' [a misconception], and I learned that ATP is an energy carrier, but it never occurred to me that it is the same molecule!"

Concerning the energetic aspect, we also discovered that students were more familiar with the concepts ATP and ADP than with the concepts GTP and "energy balance." This might be due to the fact that in high school, teachers extensively mention the ATP molecule as the energy storage compound within cells, while they tend to ignore the other nucleotides involved in energy transformation: UTP, GTP, TTP, and CTP (Storey, 1992). In addition, dATP was the most infrequent concept in students' maps, and when it was mentioned, students usually tended to believe that dATP participates in regulation of the energy balance (a misconception). In his lectures, the instructor emphasized that even though one might think that a "small letter" like "d" does not make much difference, there are major structural and functional differences between ATP and dATP.

Other interesting misconceptions concerned the concept of nucleic acids ("Nucleic acids are a type of nucleotides") and concerned the concepts of purines and pyrimidines ("Purines and pyrimidines are nucleotides").

It is worth mentioning that students' misunderstandings also manifested themselves in the analyses of the scientific accuracy of the maps. Even though most of the maps were branched and incorporated cross-links, they often included a large number of false propositions.

We believe that the major reasons for these errors are the burden of new, abstract, and complex concepts and the partial overlapping between definitions of concepts. Marbach-Ad (2001) pointed out that there is a tendency for confusion among concepts with partially overlapping definitions and among concepts that have similar names. Thus, concepts like nucleotides and nucleic acids may be remembered as synonyms. Concerning the cognitive burden of concepts, Johnstone and El-Banna (1988) claimed that, on the one hand, we have a limited ability to store and process information, and on the other hand, we are required to deal with an outsized amount of new information, in order to learn several subjects and solve problems simultaneously.

In light of these findings, we would like to offer some suggestions. First, we recommend paying attention to the hierarchical structure of the topic. For example, the hierarchy among the concepts of nucleic acids, nucleotides, purines and pyrimidines should be stressed. Second, it is vital to stress the dual role of the nucleotides in the cell as monomers of the genetic material as well as their important role in regulation of the energy balance. Finally, we suggest using concepts, such as DNA, RNA and protein, which students are more familiar with, as a platform that can subsequently be extended by branching out to other less familiar concepts like nucleic acids and nucleotides. We might suggest using visual aid, like concept maps, in order to clarify the hierarchical position of each concept and its inter-relations with other concepts.

SUMMARY

We believe that using the concept map as a tool for externalizing students' conceptions was very efficient. It did not take much time for the students to construct their concepts maps, and this enabled the instructor to gain an impression of students' understanding from his lectures. As a consequence, the instructor dealt with these issues during the course sessions. The instructor summarized the advantages of the use of concepts map in his classes on three different levels:

a) Students' concept maps may pinpoint the misunderstandings that would have been difficult to discover through multiple-choice exams. Most of these students' misunder-standings had not been experienced by the instructor in previous classes.
b) The request to select 20 concepts and arrange them in a map forced the instructor to go over his lectures and reexamine the necessity of each concept. "…I invest a lot of time in planning my lectures and I was pretty confident of my way of teaching. Talking with you [the second author] and especially having to arrange all the concepts in a map, forced me to reconsider which concepts are really important to the students. It added another dimension that I did not think of before…"
c) Exposure to the concept map technique encouraged the instructor to also start using maps as a graphic, instructional tool for summarizing his lectures, and to relate between new concepts and concepts he mentioned in the last session. "As a consequence of the exposure

to the map technique, I started to build maps and added them to my Power Point presentations as an instruction tool for summarizing specific topics."

d) Next year, as the next step of this study**,** we plan to assimilate the concept map both as an instruction tool, as well as an assessment tool in the final exam.

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