USE OF CONCEPT MAPS AS ALGORITHMIC LANGUAGE TO BUILD POTENTIALLY SIGNIFICANT TEACHING UNITS OF MATHEMATICAL OR SCIENTIFIC MODELS

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Abstract
We present a research methodology developed for the theory of scientific knowledge which use conceptual mapping, cognitive science theory, theory of didactic transposition and algorithmic language. This tool should help the identification of the constituent elements of a scientific theory, its epistemological construction, the current paradigm and the teaching methodology employed. It is suggested that in particular cases, as in the study of the theory of scientific knowledge, that conceptual mapping should be constructed under well-defined rules. Due to certain particularities of how Physical theories are constructed and expressed in terms of Physical laws we will have to generalize the tool "conceptual maps" to describe how the Physical theories are elaborated. This generalization will be called "Mapping of Scientific Knowledge Structures". We will apply this to the study of potentially significant teaching units.
Key Words: Concept Mapping, Didactic Transposition, Cognitive Theory of Science, Meaningful Learning.

1. INTRODUCTION

The main objective of this article is to present a generalization of the research tool, presentation and evaluation of the knowledge called Concept Map (CM) that we will call here Map of Structure of Scientific Knowledge (MSSK). Specifically the conceptual mapping of theories and laws of physics and chemistry as presented in textbooks in general. Thus, we will deal with the problem of presenting laws, concepts and theories in graphic or visual form and in a coherent way. In order to create a research methodology that allows the researcher in science education to compare, classify and elaborate textbooks of exact sciences in general we will show that if we create more or less rigid rules this becomes a powerful tool for the elaboration of scientific knowledge. But, physical laws are expressed in terms of statements that contain mathematical formulas. Equations (vectorial) of type $\vec{F} = m.\vec{a}$ are of central importance in physics. Names of famous scientists and experiments play a key role in spreading and characterizing certain laws. How to express them using CM?

With the subdivision of the courses of engineering and exact sciences and the explosion of the publishing market created the necessity of the production of textbooks of Physics (as calculus) for the diverse types of courses. For example, today in the USA we have physics book for calculus-based course, others for algebra-based course, etc. Each of them has a teaching methodology that differentiates it from others. Thus, it becomes interesting to have or create a tool that makes it possible to analyze and dissect how knowledge is transcribed into textbooks. The best way is the visual. If we take into account the diversity of the target audience of textbooks, it appears that a good part of them are not prepared or trained in the discrimination of the constituent elements of a model or a theory of Physics or Chemistry. So this tool will be of great value to educators as well as to students.

As a part of the current textbooks are already elaborated according to some teaching and learning methodology, and as many universities are already incorporating active learning methodologies in their pedagogical project, we will use as an example a science topic, “The Bohr model”, to show how MSSK can be used to assist in the construction of a Potentially Significant Teaching Unit (PSTU).

2. POTENTIALLY SIGNIFICANT TEACHING UNITS (PSTU)

After 40 years of research in teaching in general, some researchers as Ausubel [1977], Moreira [2013] and Novak [1990]. outlined the basic principles or elements that would constitute a teaching unit or didactic sequence that would produce meaningful learning in the sense of Ausubel [1977]. These basic principles are summarized in Moreira's article “Potentially Significant Teaching Units (PSTU) [2013]” so that we will not reproduce them in full here. Generally speaking, for a didactic sequence to be classified as a PSTU, it must take into account the students' previous knowledge, gain their interest and introduce the content and its concepts so that it articulates with the cognitive structure of the student. Briefly, a didactic sequence can be called a PSTU if it contains:

a) problem-situations that function as prior organizers and at the same time give meaning to new knowledge (Vergnaud);

b) that take into account the levels of complexity of the content to be taught and that awakens the student's intentionality for meaningful learning;

c) that this or those situations stimulate or induce the student to build, in the working memory, a functional mental model, which is a structural analog of this situation [Johnson-Laird, 1995; Nersessian, 1992];

d) The organization of education takes into account progressive differentiation, integrative reconciliation and consolidation;

e) And that it has a language that suits the students' level of understanding and encourages them to social interaction [Moreira, 2013].

3 - GRAPHIC FORMS OF PRESENTATION.

There are several ways to represent a sequence of activities, ideas, concepts, etc. The simplest one is using a flowchart. Flowcharts are graphical representations through symbols and arrows used symbolically to describe a sequence of activities, operations or actions that are encapsulated in boxes. Unlike concepts maps, they don’t has or use connector words in their boxes. Another simple way to present and organize ideas graphically would be through an organogram. Organogram is a chart that represents the formal structure of an organization. This, too, does not use binding words.

We can use synoptic picture to summarize and present ideas. The synoptic picture is a schematic summary of an idea, a text, a document, and even a teacher's lesson. Its main advantage is to allow the visualization of the structure and organization of the content that exposes a given text. It can be crafted with the help of braces, diagrams and even use a series of columns and rows as well as tables.

Another way is through semantic networks. A semantic network is a form of knowledge representation defined as a directed graph in which the vertices represent concepts and the edges represent semantic relations between the concepts. Figure 2. They are considered a common form of database readable by a machine [Uchôa, 1994].

You can also use a mind map. A mind map can be considered as a semantic network variant. In using colors and figures the emphasis is on generating a semantic network that invokes human creativity. Nevertheless, the great difference between the mental map and the semantic network is that the structure of the mental map is hierarchical, with the nodes starting from a central point. Differently, in the semantic network the nodes can be connected with any other nodes [Archela, 2004].

An algorithm is a description step-by-step and a methodology that results in solving a problem or performs a task. In general, this is represented as a resolving scheme of a problem. It can be implemented using any logical sequence of values or objects (for example, the English language, Pascal, C language, a sequence number, a set of objects such as pencil and eraser), or anything that can provide a logical sequence. Below we can see an algorithm implemented in a flowchart on the state of a lamp.

This was created and improved to make easer the task to program computers. This is based on the methodology of subdividing the task or problem. For example, we can divide systematically the problem in smaller sub-problems until we get a set of sufficiently small sub problems that allows us to solve them. In general, the algorithms are presented in the form of flowcharts before being placed in any suitable computer language.

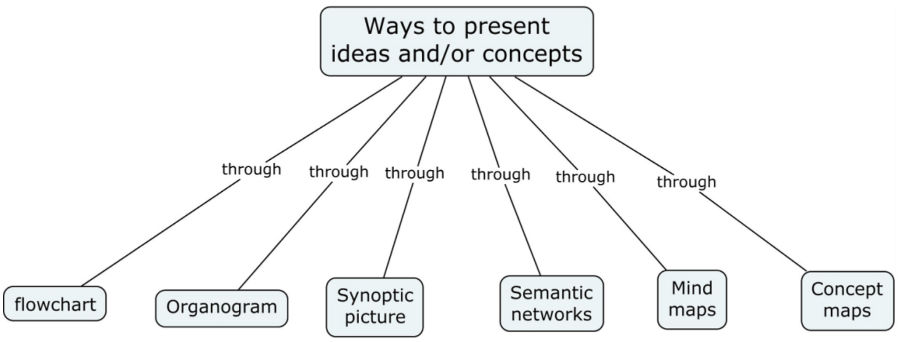


Figure 1 - Conceptual Map illustrating the most usual forms of graphical presentation of ideas and concepts.

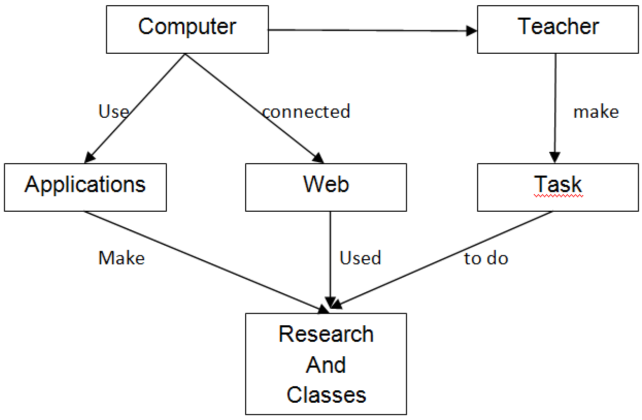


Figure 2 – Example of semantic network

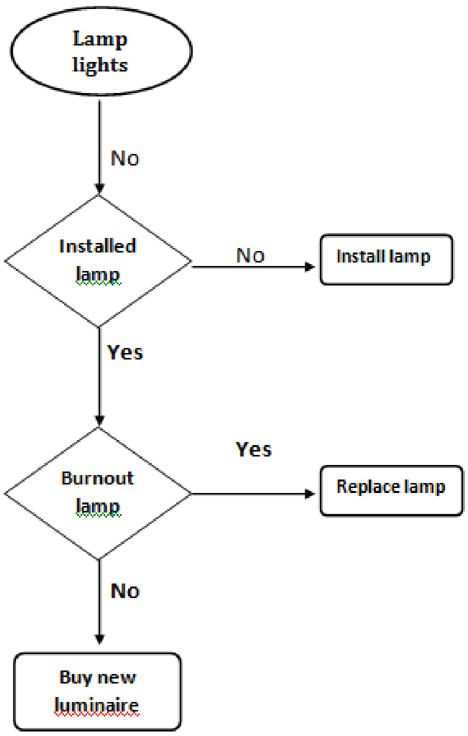


Figure 3 - Flow chart about the state of a lamp.

3.1 - Concept Maps

Concept map is a concise way to present and connect concepts [Novak, 1990; Moreira, 2005]. As this is a mapping of concepts it uses linking words to connect ideas or concepts. Due to the variety and freedom to present graphically the concepts we have that CM is the ideal tool to evaluate, present, synthesize and summarize knowledge. See figure 1 above.

It can be said that a concept plus its connector (connecting word) is the unit or element that forms or constructs a concept map. It is constructed by the unit below:

Joseph D. Novak [2006] defines in a wide manner which is conceptual maps (CM):

> *"Concept maps are graphical tools for organizing and representing knowledge. They include concepts, usually enclosed in circles or boxes of some type, and relationships between concepts indicated by a connecting line linking two concepts. Words on the line, referred to as linking words or linking phrases, specify the relationship between the two concepts."*

Due to its flexibility and degree of freedom of construction CM is one of the most used tools to represent and evaluate knowledge. As this can be constructed in the structure of knowledge more inclusive for the less inclusive, this is the ideal tool to teach significantly and / or evaluate if there was significant learning. Thus, the most common ways to build a CM are [Romero, 2007]:

1 - Spider-like Concept Map: The "spider-like" conceptual map is organized by placing the central theme or unifying factor in the center of the map. The sub-themes radiate outward circling the center of the map. Figure 5

2 - Hierarchical Concept Map: The concept map type hierarchical presents information in a decreasing order of importance. The most important information is placed at the top. Distinctive factors determine the placement of the information. Figure 4.

3 - Flowchart Conceptual Map: The flowchart concept map organizes information in linear format.

4 - System-like Concept Map: The system-like concept map organizes information in a shape similar a flowchart with the addition of 'INPUTS' and 'OUTPUTS'.

When thinking about teaching and meaningful learning the construction of conceptual maps must be done in the manner proposed by Novak and Gowin [Novak, 1998; Novak and Gowin, 1999]. In this it is considered a hierarchical structuring of the concepts that will be presented both through a progressive differentiation and an integrative reconciliation. As we will see later in the case of the study of theories and laws of Physics and Chemistry, the conceptual structure and progressive differentiation is clearer in the form of presentation of the CM in its generalization called MSSK.

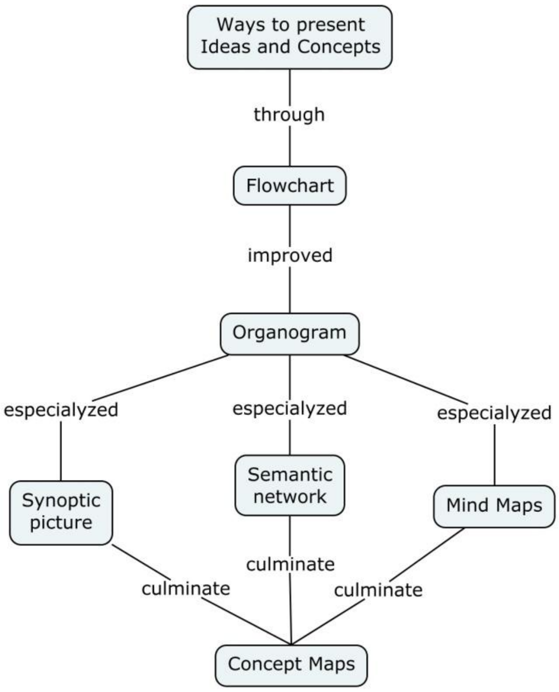


Figure 4 – Concept Map of the Hierarchical type.

When the CM is well constructed allows the visualization and perception of how the keys concepts from a particular topic or field of knowledge follow one another, intertwine and organizes themselves in the structuring of this knowledge. Thus, we tried to create some basic rules for the construction and standardization of CM's that can be seen in many articles [Novak 2006; Moreira, 2006; De Mello, 2014]. Despite these rules concept map is a very flexible tool and can be used in various ways. But, as showed by de Mello [2017a and 2017b], in the case of a systematic study we must create some very specific rules for the construction of CM, so that they become a kind of algorithmic language. This is the central theme of this article.

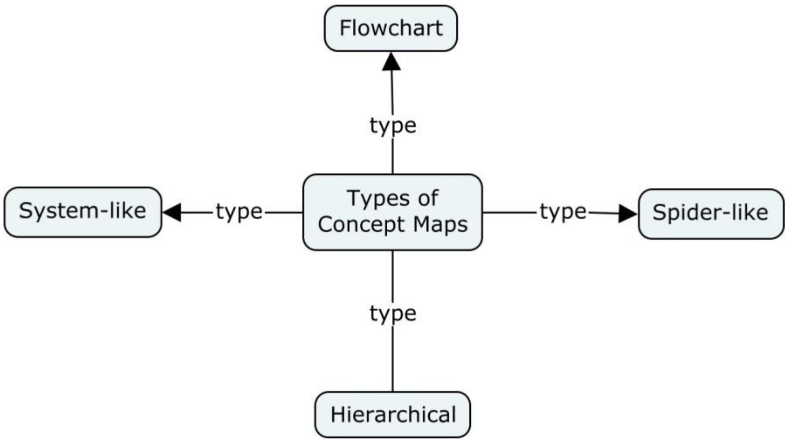


Figure 5 - Spider-like Concept Map.

CM are a powerful tool to make curricular analysis in general [Novak, 2006; Moreira, 2006]. De Mello [2020a] generalized this idea and showed that CM is the natural tool to perform the analysis of the conceptual framework that textbooks are written. But, as we said above, Physical theories are expressed in terms of mathematical equations and their functions. Therefore, we will have to briefly discuss what these are and their role in transmitting knowledge, especially school knowledge.

3.2 - Concept Maps and Physical Laws - Maps of Structures of Scientific Knowledge

When constructing a whole methodology of research to study how knowledge is generated and transmitted, in the particular case here of Physics, we have to analyze with a little more care what are concepts and connection words in a CM. In the first place, the connecting words are not restricted to mere prepositions, but these can be verbs, two words, and so on [Novak, 2006]. Without going into details of what a concept is in its more general or comprehensive definition, more details see Novak [2006] and Moreira [2005], Physics concepts are definitions based on hypotheses, laws or theories that are generally based on laws of physics which in turn are expressed in terms of mathematical functions and their equations. In Physics certain concepts gain so much importance that they acquire a proper name, for example, blackbody radiation. Let's look at this in a little more detail.

Symbols and symbolic representation of relations and operations. When we are studying or teaching concepts of kinematics the letter or symbol or sign “s” means space and is called the Physical quantities. But space in Physics means place, region with three dimensions (height, width, and depth) and is a dimensional quantity, that is, it is obtained by means of a measure by comparison with a scale (for example, a bar of one meter). In this way, a signal in physics has a series of meanings and concepts. Further details see Lindsay and Margenou [1957].

On the other hand, we have primitive and derivative quantities in Physics. That is, as in mathematics, in Physics the physical quantities are manipulated through the rules of algebra and calculus to produce or derive other physical quantities. These are called derived quantities. Through well-planned laboratory measures and strong control of external conditions we obtain functional relations and equations that describe the behavior and functional dependence of these quantities[1]. Some of these functions are so important that they are called the fundamental law of physics [Lindsay, 1957]. For example, Newton's 2nd Law: $\vec{F} = m.\vec{a}.$ Other formulas commonly denominated of law are only hypotheses, like the law of the Universal Gravitation,

$$\vec{F} = \frac{GMm}{r^3}\vec{r}$$

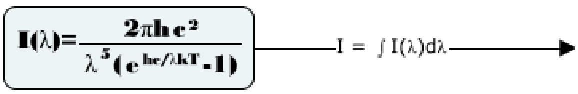
[1] For example, David Hume (1970)

Laws of Physics. A physical law is nothing more than a symbolic description (in the "simplest" form) of a routine observed in a limited field of phenomena. It is better to emphasize again its descriptive nature. He never intends to give a reason for any of the phenomena described in the metaphysical sense [Lindsay, 1957]. For example, Newton's 2nd Law tells us that when we apply a force $\vec{F}$ to a body of mass m this will acquire an acceleration $\vec{a}$. That is, it does not constitute what is popularly called explanation. Newton's law of gravitation is not an explanation of gravitation, in the sense that it explains why particles attract. It is just to give an accurate description of the observed attraction. Physical law attempts to answer the "how" question and not the "why" question. But when we put the symbol $\vec{F}$ for a physicist or student of Physics it becomes explicit all that we mentioned above and that on the right side of this expression we can substitute any of the types of forces existing in nature. Further details see Lindsay and Margenou [1957].

Physical Theory and its Construction. In order to construct a physical theory we must define its primitive concepts and symbols. In Mechanics these would be those of space (s), time (t) and mass (m); In Gas Theory would be pressure (P), volume (V) and Temperature (T), and so on. From these we obtain or construct other symbols or derived quantities. In Mechanics we have velocity (v), acceleration (a), moment (p) and others. We are then ready for the next step - the choice of hypotheses or we assume fundamental relations between the symbols by logical deduction from which all the special results of the theory, namely the laws, must be obtained. Further details see Lindsay and Margenou [1957].

Therefore, due to the hard work of systematization and definition of a concept map by the scientific community, I will have to create a particular denomination for conceptual maps in which concept boxes are made by equations, formulas, symbols or names[2]. As you might expect, we can use physics symbols when we use functions, equations, names of physics, etc as connection words. We will call these generalized concept map as "Maps of Structure of Scientific Knowledge".

Thus, if one is studying or evaluating a text whose content is the epistemological and pedagogical construction of a theory belonging to Physics one can use symbols and names of the laws of Physics in the construction of a graphical representation of this in the form of a map of the structure of scientific knowledge (MSSK). That is nothing more than a generalized conceptual map. We put down an atomic unit of this in which on one side we have the famous Planck equation connected through the integral signal (a sum over all wavelengths) to the Rayleight's Law.



In this way, it is clear to a physics teacher if the textbook was elaborated in a more conceptual manner, that is, if it omits certain mathematical demonstration or not. This is very important in the convenient choice of textbook for an exact course. In the sequence we will discuss some rules of construction of these maps of structure of scientific knowledge in order to create a tool that helps us in the construction and evaluation of didactic texts.

4. CONCEPTUAL MAPS, DIDACTIC TRANSPOSITION AND COGNITIVE MODELS OF SCIENCE.

On the other hand, scientific theories are presented in textbooks as a set of theoretical models related to some experimental facts and some identifiable measurement instruments that give meaning to the theory. Relations between the models and the facts are developed through postulates and theoretical hypotheses, which can be more or less true or false, since they have empirical content. Therefore, a scientific theory is a family of models together with postulates and/or assumptions establishing the similarity of these models with experimental facts.

These explanations, that is, theoretical ideas about the world created to understand it, are structured around concepts. For Latour [1999], these concepts, or what he calls knots or links, are those things that allow us to understand the scientific activity, without which scientific activity simply would not exist [Izquierdo, 2003]. Thus, being CM diagrams of meanings, indicating hierarchical relationships between concepts or between words that represent concepts, this are the ideal tool to map as these nodes or links are prepared and organized so as to create a coherent whole and that make sense to a certain level of schooling. That is, to study how the knowledge produced to a level of schooling is transcribed to another. More details see Novak [1990] or Moreira [2005].

De Mello [2017] demonstrates, for the case of the topic of physics called Photoelectric Effect, that currently the scientific knowledge is structured didactically in their transcriptions to textbooks in: a) models; b) the core of the theory; c) experimental facts; d) the key concepts; e) the methodology and f) the application of the theory. Thus, it is necessary to understand how these "pieces of knowledge" are inserted, deleted, and summarized to make each text a coherent whole.

De Mello [2017] showed that in the case when the original theory was built in a paradigm revolution [Kuhn, 1970] that the theory need first be consolidated in the new paradigm before suffer a Didactic Transposition (DT) [Chevallard, 1991] to the high school level. That his original

[2] I believe that it is for a short time, therefore, in essence we have a conceptual map.

explicative models must be adapt or rewritten in this new paradigm.

So, the CM built to analyze how knowledge suffer a DT must be constructed under some rules. In this the conceptual structure described above should be very clear. Like an algorithm it must be created with the finality of describe the knowledge structure. The CM builder must be trained in dissect the knowledge in its fundamental parts.

4.1 Concept Map as an Algorithmic Language to study the Scientific Knowledge.

Just as in a flowchart dedicated to computational algorithm we have specific symbols that define specific operations or actions, created in order to facilitate and standardize their reading, we have that we can create with the same objective symbols or specific colors for a particular mapping of concepts. As demonstrated by de Mello [2020a], this may be the case with MSSK designed to describe the conceptual construction with which a book, a book topic, a given field of knowledge or a scientific theory.

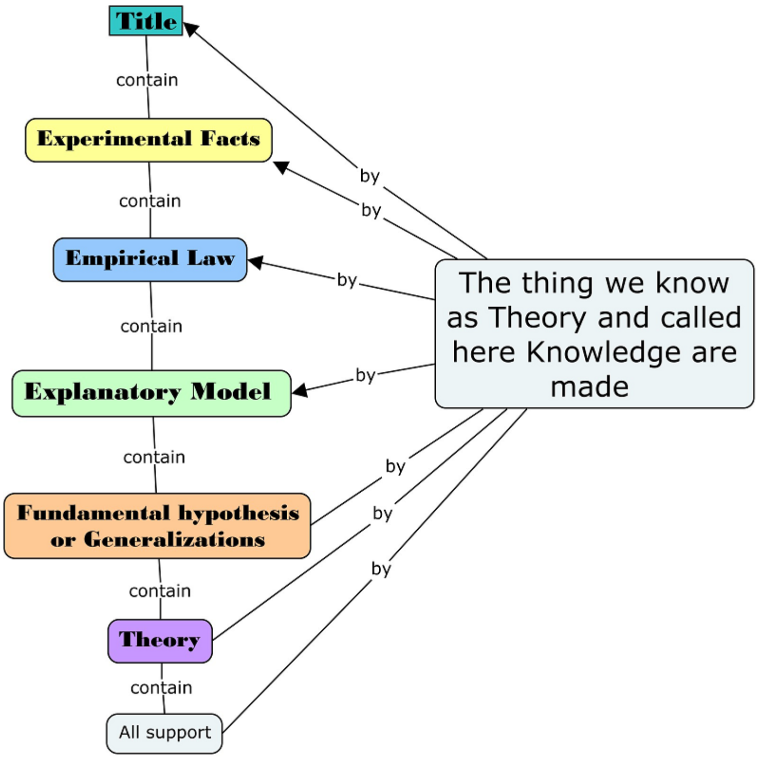


Figure 6: Figure with symbolic structure of the constituent parts of an MSSK to the theory of knowledge.

So we use green boxes to identify the models. Boxes in blue to identify empirical laws, conclusions or results. I use box in Purple for theory. We will put experimental facts that resulted in theory in yellow boxes. Title in aquamarine. Light blue all support material, such as equations, deductions, etc. Finally, we put in coral generalizations or universalizations theory. In this case we have no theory applications.

4.3 Example: Max Planck's Theory of Quantization [1901]

Many textbook authors prefer to omit the epistemological construction of the blackbody radiation theory (RCN), as is also done in the introduction to Quantum Mechanics courses. For example, we have the book Fundamentals of Physics [Halliday, 1997]. In these, Max Planck's Quantization Theory is presented, undergoing a DT [Chevallard, 1982; de Mello 2017], as simply being an ad-hoc hypothesis made by Max Planck [1901] to explain the blackbody radiation (RCN) spectrum. There is no exposure of explanatory models or experimental facts that resulted in the theory. There is no exposure of explanatory models or experimental facts that resulted in the theory. They simply need the equation that relates energy to the frequency of light. That is, it contains all the necessary information and concepts and they simply present Planck's constant and the equation

$$E = h.\nu$$

In some texts, mainly to train engineers in general, this theory is presented briefly. That is, the definition of RCN (boxes in light blue) is summarized, the presentation of the empirical Laws that preceded Planck's Law (boxes in blue) and its hypothesis (box in caramel). As an example of this type of text we have the book Modern Physics [Young, 2005]. There is no elaboration of an explanatory model, nor a discussion of how it was elaborated in the old paradigm. See fig. 7. Apparently this is another example of a textbook CM. But it is a MSSK, because the boxes were colored to differentiate the concepts, the Physical laws (empirical laws), the hypothesis and the final theory.

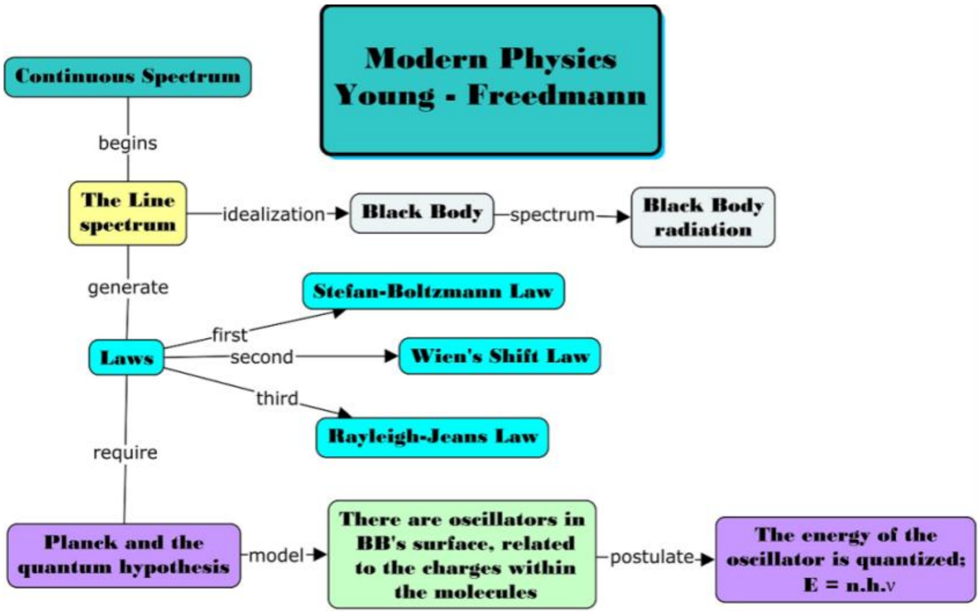


Figure 7: The MSSK of BBR theory from the text of Young-Freedemann textbook [2010].

In the figure below we have the CMSK from the Glencoe section "Radiation of Incandescent Bodies" for US high school. This is an open e-book (Free) designed to be used with problem-based active teaching methodology and at any of the three levels of American education (basic, high school and honor). So it starts by presenting students with the problem (prior organizer) of understanding or explaining the radiation spectrum of an incandescent body (Box in gray). Then they do an experiment with an incandescent lamp (Box in yellow) emphasizing the relationship between temperature and the maximum color emitted by the lamp (creating a mental model). They don't present a physical model, as is common in American education. Only after motivation does them present the quantization hypothesis (Box in almonds) and theory (Box in purple). In this way, an MSSK presents how school scientific knowledge was constructed, as well as how it should be presented or taught.

We see in the example above, figure 8, how, through a riddle and a very simple experiment with an incandescent lamp, the authors introduced the problem of studying the light spectrum and at the same time using a very simple language suitable for the level of understanding of the students. Through the problem situation they suggest how to organize the key concepts of the theory and stimulating the interaction - questioning - between the students. But at the high school level as well as at the university level, the presentation of this theory does not allow for a more elaborate mathematical demonstration so that we need to make a progressive differentiation of information. Let's look at an example of a PSTU.

4.4 Example: Bohr's Atomic Model

In the project Glencoe [2005], problem-based learning, they start by posing the problem of determining how the matter would be distributed in the atom (Gray box). They retrace the historical path until they reach the Bohr model in order to define a common language and a mental image of the atom with the students and sharpen their curiosity. Through the presentation of the Rutherford model they introduce the idea that the electrons must be rotating around the atom and connected to it by Coulomb's force. In this way, the atom should be emitting Electromagnetic radiation and, therefore, it would be unstable. In this way, they begin to progressively differentiate the concepts involved in the construction of the Bohr model.

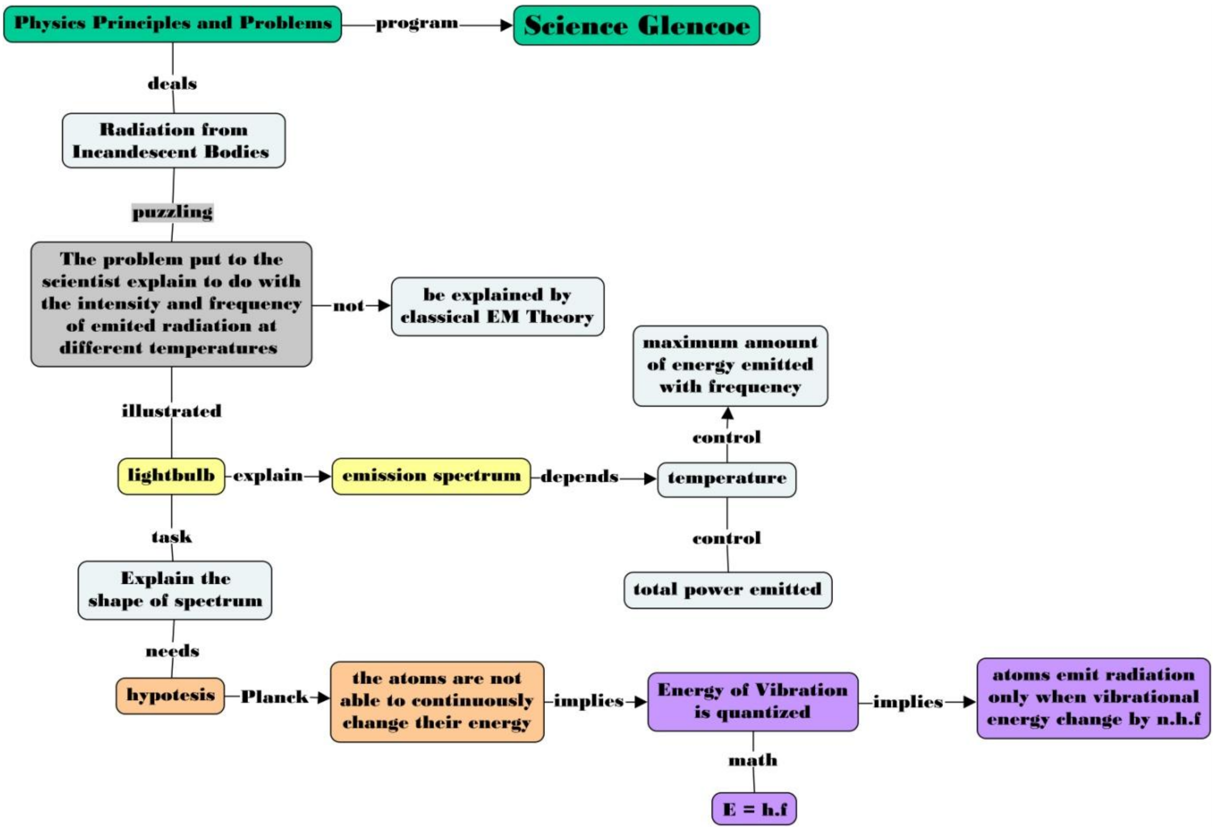


Figure 8 – MSSK da seção Radiação de Corpos Incandescentes do livro Glencoe.

They introduce the idea or concept of energy quantization through Bohr's three postulates (caramel boxes). Then they return to the physical model that the electrons must rotate around the nucleus and remember the concept of energy conservation (Box in light blue). In the sequence they present the spectral lines of the hydrogen atom (Box in yellow) as the experimental fact to be explained. In the green boxes they make the progressive differentiation of the mathematical concepts that should be integrated, solve the equation, to obtain the Rydberg formula that relates the wavelength (frequency or Energy E_n) with the inverse of the square of the integer n that determines the electron orbit (purple boxes).

Below we place the MSSK explaining the Bohr model emphasizing the philosophy and concepts of Physics. Comparing with Glencoe's MSSK we take the historical introduction or the problem that motivated the problem. As we wish to emphasize that this model must explain or obtain Rydberg's formula, we explicitly put it (Light blue box), which is omitted in Glencoe. Another important fact, making a connection with the philosophy of science, is that the equations of energy quantization and angular momentum are presented here as postulates to emphasize that these were not yet accepted - old paradigm. In Glencoe, they appear as laws to reinforce the idea that they are fundamental stones of the quantum mechanics paradigm. Here it was emphasized that the Rydberg constant is an experimental result that is explained in the Bohr model. That is, in the Bohr model this is calculated using other primitive concepts. Together with the Rydberg constant box (yellow), the primitive concepts, Light blue Box, are connected.

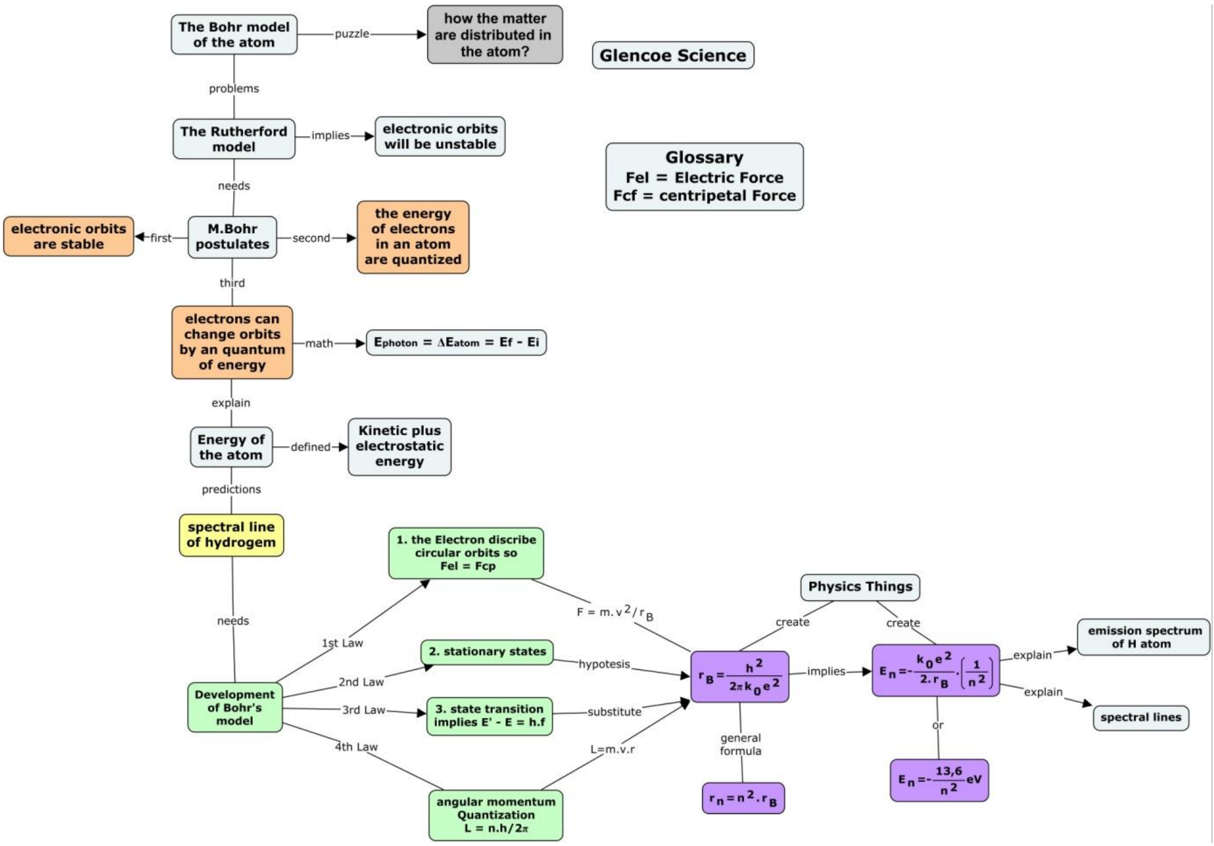


Figure 9 – The Bohr's Atomic Model, Glencoe Project

It should be noted that the Glencoe project [2005] is a pedagogical project aimed at high school so that through a problem situation they build a mental model of the physical situation. From these, they gradually present the physical concepts with increasing complexity, until the time comes to solve a system of linear equations. That is, they remember the concepts of dynamics and kinematics until the moment of calculating the Bohr radius. In this way we use two equations as connection words when presenting the Box of the Bohr radius. These equations make the connection between Bohr's laws and its radius.

In the presentation below we use the experimental fact of having well-defined spectral lines suggests the postulate of the atom to have well-defined orbits. From this postulate, there is a progressive differentiation and a parallel between the cinematic and dynamic concepts related to circular movement until the moment of the introduction of the postulate of quantization or paradigm change. Using the equations of forces and angular momentum as connecting words between dynamic and kinematic concepts, the concepts are integrated by obtaining the formula for the Bohr radius (boxes in green).

Results and Conclusions

Through the recall that behind traditional physics symbols such as s, v, t, F, h, etc., there is a whole wealth of content and concepts that can be used now as connecting words and sometimes as concepts in a conceptual map. The same is valid for quantities derived from these as functions, equations, names of theories and models. As these ideas have not yet been widely accepted in the scientific community, for now we will refer to these conceptual maps as maps of structures of scientific knowledge (MSSK).

Here we try to show the advantages of creating rules to the construction of conceptual maps with the use of color coding. From these rules we provide the CM with an algorithmic structure so that we denominate it in the text as MSSK, to distinguish it from the CM prepared without the use of this structure.

With the use of MSSK we were able to show as the knowledge produced in the academic spheres will suffering a DT, that is, is transformed and diluting to get to school class (sphere). Using CM as an analysis tool for the knowledge study we reduced the degree of subjectivity of this analysis and make it easy to identify, classify and order the elements of a given scientific knowledge or theory, as we are accustomed to call. The MSSK facilitates the dialogue between scientific communities. This allows, for example, that a physicist when teaching a Physics course to engineers realizes which points he will have to emphasize and which ones they can suppress or not evaluate. In this case, you can emphasize the dimensional analysis (primitive concepts) and suppress the theoretical models.

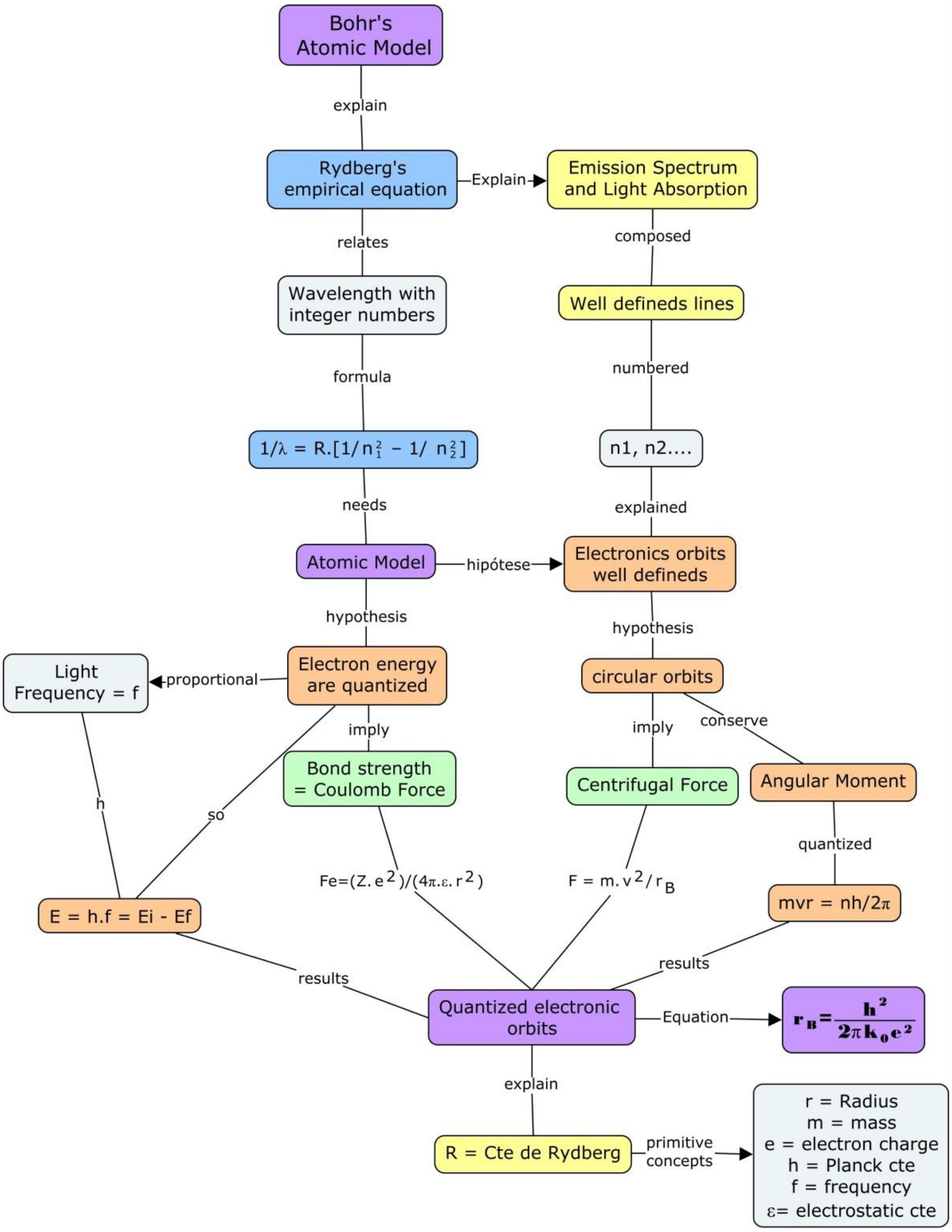


Figure 10 - Bohr's Atomic Model

The CM in the form of algorithm (MSSK) will indicate which sequence the author entered, organized and braided the component parts of his theory (knowledge). Moreover, MSSK analysis done for a particular book allows you to view how these concepts (or nodes or links) are inserted, deleted, summarized and twisted to make each text a coherent whole [de Mello, 2017 and 2020b]. Used in a comparative analysis it allows you to check: a) as explanatory models are adapted, simplified and deleted; b) how knowledge of the contents are transposed into a teaching methodology of science, suffering a didactic transposition; c) when and how knowledge is implemented and consolidated in a new scientific paradigm, and finally, d) it facilitates the construction and study of a PSTU.

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