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WHAT ARE MY STUDENTS LEARNING WHEN THEY CONCEPT MAP?

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Abstract. Concept maps are used by educators all over the world as a learning tool. In addition to help learn subject-matter content, concept mapping is considered to develop higher-order thinking skills. However, concept mapping is used most commonly as an assessment tool, and set within an activity that usually does not involve learning. Depending on how instructors use concept mapping with their students, they can facilitate increased learning of both subject-matter content and higher-order thinking skills, or it can be an activity with little impact in the students' learning. In this paper we discuss under what conditions concept mapping can lead to learning, and what it takes for the students to get there.

Keywords*:* concept maps, higher-order thinking skills, learning, subject-matter content knowledge

1 Introduction

Since its invention in the 1970s by Joseph Novak and his research team at Cornell University (Novak & Gowin, 1984), concept mapping has been proposed as a learning tool. Numerous studies have shown how concept mapping can enhance learning (Khodadady & Ghanizadeh, 2011; Martínez, Pérez, Suero, & Pardo, 2013) and our experience corroborates that, when used properly, concept maps are a valuable learning tool. Concept mapping has also been examined and used extensively as an assessment tool in many subject areas (e.g., Anohina-Naumeca, 2015; Buldu & Buldu, 2010; Jacobs-lawson & Hershey, 2002; McClure, Sonak, & Suen, 1999; Reiska, Soika, & Cañas, 2018; Robinson, 1999; Ruiz-Primo; Stoddart, Abrams, Gasper, & Canaday, 2000; Walker & King, 2003). In this paper we are interested in the use of concept mapping for learning. More so, we are interested in what is it that we learn when we construct a concept map? We propose that the amount and type of learning depends on how the concept mapping construction takes place.

2 Higher-Order Thinking Skills vs Subject-Matter Content

The TIMSS (Trends in International Mathematics and Science Study) assessment framework (Mullis & Martin, 2013) defines two kinds of domains: (1) content domains (subject knowledge) and (2) cognitive domains (thinking processes). In the TIMSS framework, content domains include subjects such as mathematics, biology, physics, chemistry, and social studies. The cognitive domains include knowing, applying and reasoning. They conceive knowing as a student being able to recognize concepts, relationships etc., recall and describe them and can give examples. The second cognitive domain, applying, regards the student as being able to apply "knowledge of facts, relationships, processes, concepts, equipment, and methods in context" (Mullis & Martin, 2013, p. 56). The third cognitive domain, reasoning, means that student can "analyze data and other information, draw conclusions, and extend their understandings to new situations. In contrast to the more direct applications of science facts and concepts exemplified in the applying domain, items in the reasoning domain involve unfamiliar or more complicated contexts" (Mullis & Martin, 2013, p. 56).

The authors of the TIMSS 2015 Science Framework are of the opinion that the cognitive domain can't be assessed in isolation, but must be assessed in context of the content domain (Mullis & Martin, 2013). Tricot & Sweller (2014) are of the same opinion. They distinguish between two domains: domain-specific knowledge and domain-general knowledge. They define domain-specific knowledge as memorized information and domain-general knowledge "can be used to solve any problem in any area" (ibid, p. 279). They conclude that teaching only domain-general knowledge is not possible and at schools should continue to focus mainly on domain-specific knowledge.

As Agarwal (2018) has stated, educators and researchers have long argued whether higher-order learning can be developed directly or whether, as in progressing through Bloom's Taxonomy, it needs to be based on factual knowledge. She (ibid, , p. 1) found out that "students' higher-order learning increases most from higher-order retrieval practice, or no-stakes quizzes with complex materials that engage students in bringing what they know to mind.

Although fact quizzes were beneficial for fact learning, they did not facilitate higher-order learning, contrary to popular intuition based on Bloom's taxonomy."

In this paper, we'll refer to the content domains, the domain-specific domains and factual knowledge as subject-matter knowledge, while we'll include the cognitive domains, domain-general knowledge and higher-order learning within the broader higher-order thinking skills (HOTS) term.

3 Learning while Concept Mapping

As stated earlier, learning occurs on two domains, subject-matter content and higher-order thinking skills. We will first analyze the learning of subject-matter content and then expand to learning and exercising higher-order thinking skills.

3.1 Learning Subject-Matter Content

Anywhere during the progress of a teaching/learning unit or module, the instructor might ask students to carry out concept mapping (Cmapping) activities. There are many types of Cmapping activities or tasks that the instructor can choose from (Cañas, Novak, & Reiska, 2012; Ruiz-Primo, Shavelson, Li, & Schultz, 2001; Strautmane, 2012). The purpose of the activity, e.g. whether it involves learning or assessment, is individual or in groups, helps the instructor determine the type of activity. For example, it could consist of asking to students to construct a Cmap starting from a given list of concepts or a focus question to answer, in order to assess prior knowledge at the beginning of the unit. This would help the instructor ascertain which students have problems with concepts that should already be understood and which students already understand concepts that are to be covered in the unit (Mason, 1992; Rebich & Gautier, 2005). In this case, students would be expected to construct a concept map based on their prior knowledge, so no learning is expected. Similarly, students could be asked at the end of a unit to perform a Fill-in-Cmap task (Schau, Mattern, Zeilik, Teague, & Weber, 2001; Soleimani & Nabizadeh, 2012), where a previously constructed Cmap on the subject-matter has some of the concepts and/or linking phrases left black and the student needs to fill in the blanks. This is meant to be an assessment task, not a learning task, and so there is no learning of any kind expected or involved. Similar type of assessments, such as presenting Cmaps with errors for students to correct, or multiple-choice Cmaps (Correia, Cabral, & Aguiar, 2016; Moon, Johnston, & Moon, 2018) don't result in any learning either.

Subject-matter learning would be expected if the instructor asks students, for example, to construct a concept map about a particular topic and gives them time to consult other resources (the Web, textbook, peer students, etc.) during construction of the concept map. Students will need to study and learn aspects of the subject-matter that they don't fully know or understand and that prevent them from completing the Cmap. As the student constructs the Cmap, subject-matter learning takes place. Selecting the concepts that go in the map, analyzing their relationships to determine the most appropriate linking phrases, and defining the hierarchical relationship between the concepts, for example, requires understanding the subject-matter and most likely involves learning.

Figure 1 shows a "subject-matter knowledge" line that depicts the amount of subject-matter knowledge a student, or group of students, have on a topic. The further right on the line, the more subject-matter knowledge. On the left endpoint is the subject-matter knowledge that students have about the unit's topic at the beginning of the unit. Along the middle is the subject-matter knowledge expected at end of the unit.

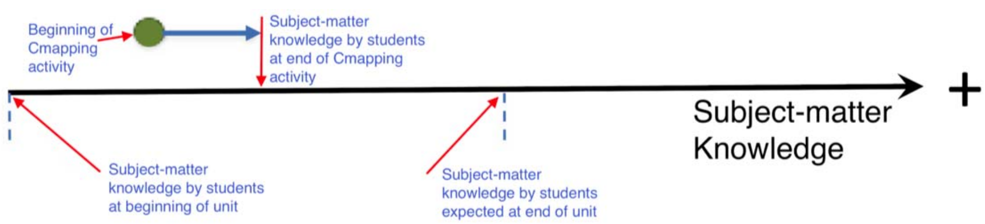

Figure 1. Students' subject-matter knowledge about a particular topic increases as a result of a Cmapping activity.

As discussed above, a Cmapping activity that involves constructing a concept map will most likely result in an increased understanding of the subject-matter, that is, will result in subject-matter learning. The green circle in Figure 1 shows the subject-matter knowledge at the beginning of a Cmapping activity, and the arrow depicts the “amount” of learning resulting from the activity. How much learning takes place (i.e. the length of the arrow) depends on many aspects, including the way the Cmapping activity is set up. We’ll discuss these below.

3.2 Learning and Exercising Higher-Order Thinking Skills

During the construction of a concept map, the organization of the concepts and construction of the propositions is an iterative process where the concepts are moved around, modified, added and deleted and the linking phrases are added and refined. The map constructor at this point is constantly analyzing – a higher-order thinking skill – whether the latest (or next) actions (move the nodes around, add a linking phrase, etc.) best represents his or her understanding of the topic. Time is often spent on thinking which of several possible linking phrases best reflects the relationship between two concepts. The linking phrases are often replaced by a better alternative, concepts may be added, deleted, or moved around, and the big ideas – the most relevant concepts of the map – may become evident as the map is constructed, if they haven’t already. This construction and refinement process is one of reflective thinking, a higher-order thinking skill. Thus, during of the construction of a concept map, not only subject-matter content is learned, but higher-order thinking skills are learned and exercised.

Figure 2 shows the subject-matter knowledge line from Figure 1 in the x-axis, and has at the y-axis a similar higher-order thinking skills line, where moving up the y-axis implies increased higher-order thinking skills. This higher-order thinking skills line has a different time frame than the x-axis. While the x-axis represents the subject-matter knowledge for a unit, module or course, the development of higher-order thinking skills is assumed to be long-term, skills that are aggregated through different subjects and throughout the years. In the graph on the left, the green circle is at a position that shows that there had been learning in both subject-matter content and higher-order thinking skills before the Cmapping activity began. For simplicity, in this paper we will normalize the Cmapping activity and have it start at the origin of the graph, as in the graph on the right in Figure 2. As in Figure 1, the length and slope of the line representing the increase in knowledge should be taken as an indication or approximation based on our experience and the literature and should not be taken literally.

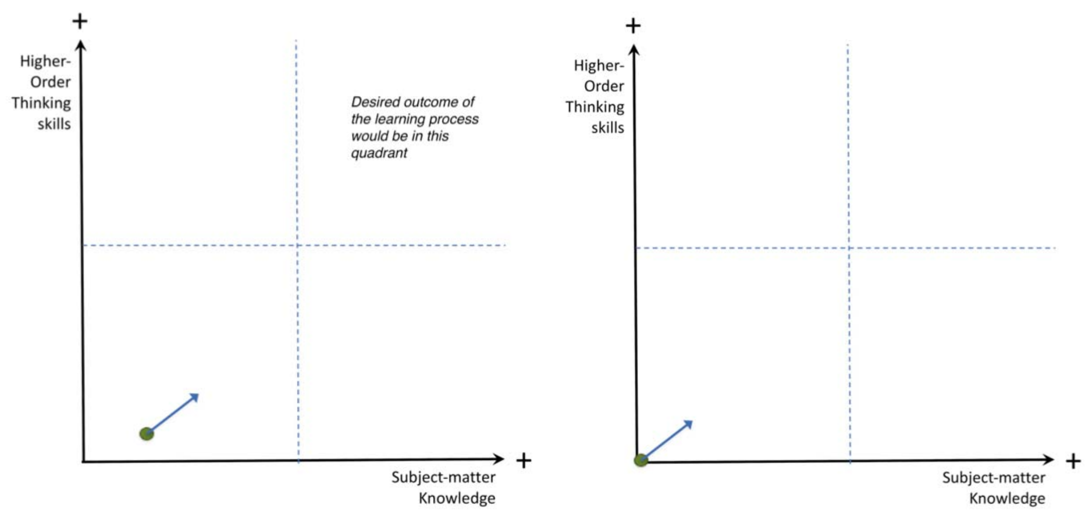

Figure 2. In the graph on the left, students’ subject-matter knowledge about a particular topic and higher-order thinking skills increases as a result of a Cmapping activity during the development of a unit. On the graph on the right, we have moved the Cmapping activity to the origin of the graph, and we’ll use this representation throughout the paper.

The development and exercise of higher-order thinking skills during a Cmapping activity, just as with the learning of subject-matter content, depends on the settings for the Cmapping activity. We will discuss three sets of conditions: (a) the instructions given to students, (b) how good Cmappers the students (and instructor) are, and (c) whether concept mapping is done as a process.

4 Cmapping Activities

4.1 Task Conditions

Every Cmap should respond to a focus question (Novak & Cañas, 2008), which provides the reference or context for the map, and guides the students who should make sure the Cmap responds to the question. Unfortunately, very often the students are not provided a focus question, and left to 'guess' what the instructor really wants on the map. By having a focus question to work with, and knowing the instructor will be assessing whether the Cmap responds the question, guides the student to ask him or herself, "does the concept map answer the focus question?", a process that requires not only reflective thinking, but also evaluation, two higher-order thinking skills.

In addition, a dynamic focus question may lead to more explanatory concept maps (Derbentseva, Safayeni, & Cañas, 2006a) and cyclic concept maps (Safayeni, Derbentseva, & Cañas, 2005). A dynamic focus question usually provokes concepts being events instead of objects, which leads to dynamic propositions, resulting in explanatory instead of descriptive concept maps, which are considered to show deeper understanding (Cañas & Novak, 2006). By providing a good focus question, the instructor is able to lead the students to construct explanations – a higher-order thinking skill – which requires deeper understanding, and thereby lead to increased subject-matter learning.

Providing the student with the root concept of the concept map as a starting point is not a common condition even though research has shown that providing a quantified root concept has a stronger effect on the resulting concept map than providing a corresponding focus. Furthermore, providing both a dynamic focus question and a quantified root concept leads to more dynamic thinking and results in explanatory concept maps (Derbentseva, Safayeni, & Cañas, 2006b), again requiring that the student provide explanations instead of descriptions and leading to increased subject-matter learning.

Besides providing a focus question, a root concept, or both, the instructor can give the students a list of concepts to include in the concept map, as we mentioned in a previous section. The list of concepts could be used to assess prior knowledge, in which case no learning is expected. Or they could be concepts being introduced in the unit or module, maybe complemented by concepts students should already comprehend, and the students must construct the Cmap as they learn how the concepts are related as they aim to answer the focus question. It is not clear whether there is more learning of subject-matter content of higher-order thinking skills when provided by a list of concepts, but experience and research has shown that the same students construct better maps when given a list of concepts than under no conditions, and better maps than when provided with a text that includes the concepts (Soika, Reiska, & Mikse, 2012).

Figure 3 depicts how much learning of subject-matter content and development and exercise of higher-order thinking skills can be expected from the construction of a single concept map. Even with a good focus question, other conditions have a higher impact on the amount of learning that takes place during a Cmapping activity, as is discussed below.

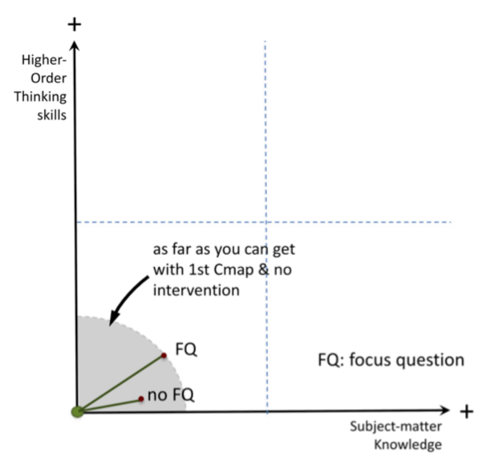

Figure 3. The learning in subject-matter content and development and exercise of higher-order thinking resulting from the construction of a single Cmap, with and without a good focus question, and no interventions.

4.2 *Are My Students Excellent Cmappers?*

Figure 3 assumes that the students can construct good Cmaps, more so excellent Cmaps as explained below, given a good focus question or root concept. However, our experience is that most students never reach the point as a Cmapper (a constructor of Cmaps) where they really use concept mapping as a learning tool and as a tool to develop higher-order thinking skills (Cañas, Reiska, & Möllits, 2017). In fact, we believe that Figure 3 is pretty optimistic in terms of what you can achieve with the construction of one single Cmap, as we will explain.

Cañas, Novak & Reiska (2015) introduced the distinction between good and excellent Cmaps, and thus good and excellent Cmappers. A good Cmap has a good structure and good content. An excellent Cmap, not only responds to the focus question, it explains the response in a clear fashion. Excellent Cmaps are explanatory, not descriptive. They are concise, and don't have superfluous concepts, linking phrases or propositions that are not relevant to the topic or don't help answer the focus question. They are clear and communicate the key ideas. Constructing an excellent Cmap requires a clear understanding of the topic being mapped. If the Cmapper is an expert in the subject area, then there might be no subject-matter learning involved. But if the Cmapper is a student who started building the map when he or she didn't know the subject, and the construction of the map was part of the learning process, then clearly subject-matter learning took place. We mentioned above that constructing a concept map involved higher-order thinking skills, including analyzing, reflective thinking, evaluation and explanations. Expressing knowledge in the most concise and explanatory way involves a high level of synthesis – a higher-order thinking skill. Good, well selected crosslinks, which link concepts from different subdomains of the concept map, are a key aspect of excellent Cmaps. Crosslinks are often considered to show broad understanding and have been referred to as representative of creative leaps on the part of the Cmap constructor and are considered important in the facilitation of creative thinking (Novak & Cañas, 2008), a higher-order thinking skill. Presence of good crosslinks in their Cmaps reflect broad understanding of the topic on the part of the students. Overall, constructing an excellent Cmap, particularly one for a topic which the student is learning, involves a substantial amount of higher-order thinking skills. Figure 3 actually reflects the learning, both in subject-matter content and higher-order thinking skills, for students who are Excellent Cmappers.

Getting to build good Cmaps is hard, and getting to build excellent Cmaps much harder. It takes time and practice to become an Excellent Cmapper. There is a learning curve in constructing Cmaps that is usually reflected in the concept map's size, as shown in Figure 4, which show the size of the Cmaps from the time persons starts concept mapping to the time they reach Excellent Cmapper (Cañas et al., 2017). New users who are learning what Cmaps are about and possibly at the same time learning how to use the software tool to construct them will initially build small maps. Often the initial struggle is figuring out what concepts are, what are linking phrases, and what are propositions. As they become more comfortable with the process of constructing a concept map, their maps become larger, as now the struggle is with the content. Users ask themselves what concepts are missing, and whether the concept map is large enough. Typically, at this point users are figuring out that coming up with the best linking phrase to construct a proposition is among the hardest parts of building a concept map. At this point are approaching the point where they can build Good Cmaps. In terms of Figure 4, they are still to the left of the dotted line.

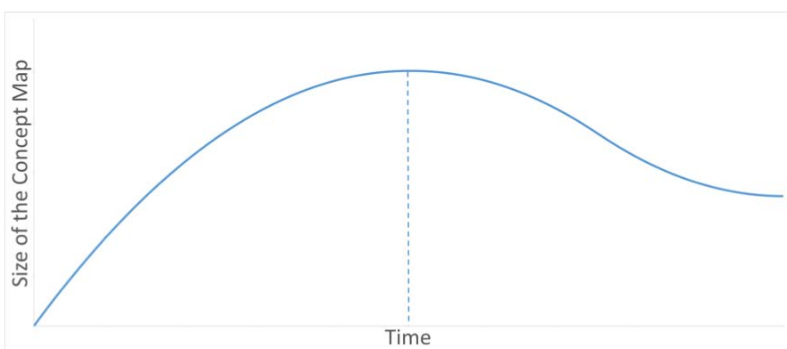

Figure 4. The time it takes to reach Excellent Cmapper as reflected in the size of the Cmaps built, from Cañas et al (2017).

Users who continue building concept maps, and who get feedback on their maps, will begin to spend time thinking about their maps in terms of the key features of Excellent concept maps: are the main, key concepts and ideas clearly represented? Does the map clearly respond to the focus question? Are all concepts and propositions relevant to the topic and help answer the focus question? Are all relevant concepts included? Is every linking phrase the best option to express the relationship between the particular concepts? Could the same explanation be presented in a more concise map? As these questions become second nature to the Cmapper he or she is moving through the point in time depicted by the dotted line in Figure 4, becoming an Excellent Cmapper, and the mapping process now requires more of the higher-order thinking skills described above. The concept maps become smaller – in concept mapping, larger is not always better (Kinchin, 2014).

Unfortunately, most students never reach the tipping point of the curve, they remain to the left. This means that they don't benefit from the development and exercising of higher-order thinking skills and the learning of subject-matter content that excellent concept mapping can foster. Many authors have written that concept mapping is easy to learn and use (Fiedler & Salas; Wei & Yue, 2016). Bixler et al. (2015) report that when provided concept mapping in a modest dose, students were not able to improve critical thinking skills, but students perceived the process of concept mapping as easy to use and learn. But this simple construction is way at the left of the dotted line.

The most common use of concept mapping is for instructor's assessment of students' subject-matter content. Students are usually given one chance to draw the map, as part of an assignment or test, and the instructor evaluates it. Given the tendency of assessment rubrics to rely on structural measurements (Kinchin, 2014), students will figure this out and tend to build as large a concept map as possible with as many crosslinks as they can figure out. Seldom do they get any feedback on the quality of the maps, or the opportunity to revise them. Often, they are only given a few minutes of introduction on concept mapping before being asked to construct the concept maps. This setting does not lead to developing students as Excellent Cmappers, and leaves them on the left of the dotted line in Figure 4.

On the other hand, students who are given the opportunity to work on their maps as they learn the subject-matter and get feedback from the instructors and peers will begin to apply their higher-order thinking skills, resulting, for example in discriminating between key and irrelevant concepts, their maps becoming better built structurally and content-wise, and more precise, as was reported by Dowd, Duncan & Reynolds (2015). To make sure that their students are learning subject-matter content and developing and exercising higher-order thinking skills during their concept mapping sessions, instructors need to make sure they have the practice and support to become Excellent Cmappers.

4.3 Concept Mapping as a Process

Excellent student Cmappers can learn substantial subject-matter content and develop higher-order thinking skills while they individually construct their concept map, and not yet reach the full potential of concept mapping as a learning tool. To achieve the full potential, concept mapping in the classroom must be seen as a process, as part of the whole learning activity, and not as an isolated task.

Consider the case mentioned in a previous section, where at the beginning of the unit or module the instructors give their students a list of concepts and ask the students to construct a concept map with those concepts, as a way to assess prior knowledge. Let's assume that initial concept map was based on a good focus question. Now, what if those initial concept maps are not discarded, but used as part of the learning process for the unit. The students would get feedback on their concept map, and would be asked to enhance the map as they learn more about the subject-matter content. Most likely the concept map did not have all concepts well linked and integrated (i.e. it was not an Excellent Cmap), but it can be taken as the starting point to learn about the subject matter. The concept map could guide the search and for information, e.g. concepts that the students didn't know or understand well, and then content learned would be used to enhance the map, which would reflect the increased understanding and learning. If the software tool being used to construct the concept maps allows it, e.g. CmapTools (Cañas et al., 2004), resources and concept maps can be linked into a Knowledge Model. At the end of the unit, the concept map(s) (particularly when compared to the initial map), would be evidence of the learning that took place. Novak & Cañas (2004) refer to this as a New Model of Education. The construction of the concept map(s) is a *process*, it's not a single-shot action

There are many changes in the conditions in which a concept map is constructed that can lead to increase in learning of subject-matter content and higher-order thinking skills. One of them is having the concept map built in small groups of students. While constructing a concept map as a group, students must carry on a negotiation of meaning, in particular during the construction of propositions. This meaning negotiation, in fact, is one of the richest subject-matter content learning aspect of concept mapping, and leads to a constant argumentation, a higher-order thinking skill, among students and between the student(s) and the instructor. We reflect this increase in learning in Figure 5. With the group work, the amount of subject-matter content and higher-order thinking learning would increase.

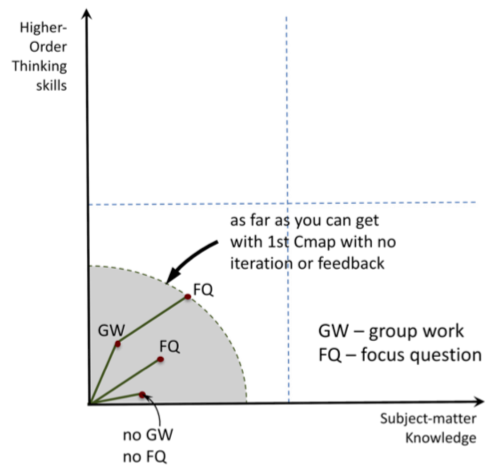

Figure 5. The learning in subject-matter content and development and exercise of higher-order thinking resulting from the construction of a single Cmap, without a focus question, with focus question, and group working with focus question, and no interventions.

Concept mapping as a process involves a series of interventions. Each of these interventions results in a subsequent modification to the concept map. An intervention could be a question that leads to the modification of the map. For example, as the students are building their concept maps, the instructor could come by and ask them questions about the map. Even when given a focus question, during the map construction other questions will arise, not only from the instructor, but also map constructors themselves or from fellow students that will lead to the expansion of the maps or construction of other maps. The process of construction should be a continuous questioning between the student and the instructor, a higher-order thinking skill.

We refer to one or more interventions and the subsequent modifications on the concept map as an iteration, such that concept mapping as a process is a series of iterations from the initiation of the construction of the concept maps to when they are done (which don't necessarily match the beginning and the end of the unit or module).

Different types of interventions can lead to different quality of iterations. For example, automated quantitative feedback on the structure or topology of the concept map could be considered a low-quality intervention. Simple feedback from the instructor would be a somewhat higher quality intervention. While an extensive group discussion on the content and structure of a concept map and whether it responds to the focus question would be a high-quality intervention. Iterations involving questioning, feedback and critique interventions by the instructor and peer students, together with group discussions on the concept maps constructed by teams of students, who are constantly collaborating and negotiating in their teams, can result in increased subject-matter content learning and increase development and exercising of higher-order thinking skills. Among other possible interventions, we include argumentation, searching for information, presentations, etc. Figure 5 shows how low-quality iterations result in little increases in learning while high-quality iterations will result in larger increases.

Even simple feedback can be motivating to students. In an experiment carried out by Miller et al (2010) with elementary school students in Panamá, students were so excited that experts remotely annotated their concept maps, that even if the feedback was just complimentary and not content-related, they were motivated to continue working and improve their maps, and their resulting Cmaps were just as good as those of students who received content-related feedback, in contrast with students who did not receive any feedback at all and did not feel motivated to continue working on their maps. Pérez Rodríguez et al (2006) report on the use of several iterations that involved peer feedback and commenting by groups of university students in a physics course, resulting in an increased learning compared to the traditional teaching method. Chiu et al (2000) found in an experimental study on collaboration during concept map construction that the greater the interaction, particularly high-level interaction processes, the better a group performed. And De Simone et al (2001) write that during a collaborative concept mapping study, participants said that concept mapping provided them with clear, concrete feedback for self-evaluation and facilitated the role of group sharing and discussion, and suggested that groups should present their map to the whole class for critique. They wanted more feedback on what makes a good map, and constructive, ongoing feedback on both the mapping process and their subject-matter content understanding.

The combination of Excellent Cmappers with high-quality iterations leads to increased subject-matter content learning and development and exercising of higher-order thinking skills. It takes time to get students to construct excellent concept maps, and generating quality interventions also takes time, practice and experience. But once an instructor has all these conditions together, students during their concept mapping activities will be able to achieve the level of subject-matter content and higher-order skills learning on the top-right quadrant as shown in Figure 7.

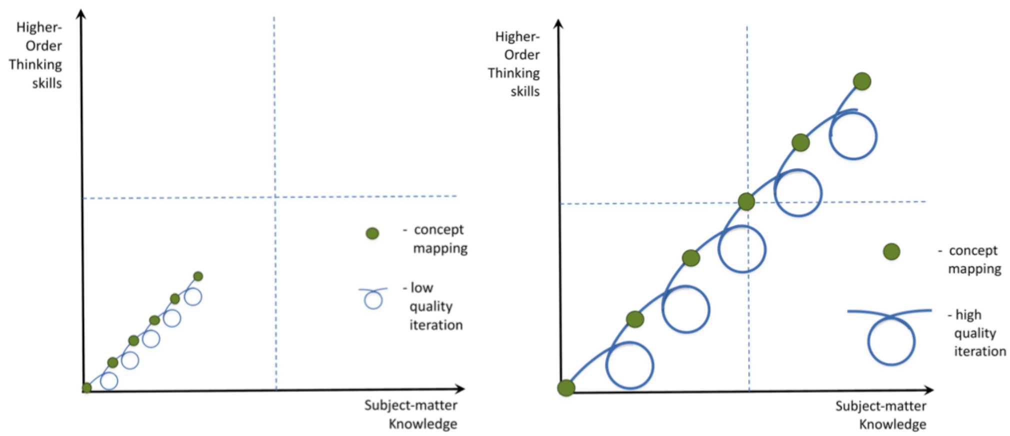

Figure 6. On the left, low-quality iterations result in small amounts of increased learning, while on the right high-quality iterations result in larger amounts of increased learning

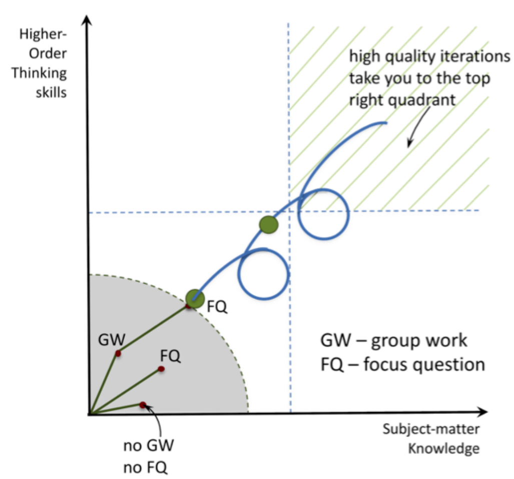

Figure 7. Excellent Cmappers learning though high-quality iterations can reach the top-right quadrant.

5 Conclusions

The literature and our own personal experience have taught us that concept mapping can lead to increased subject-matter content learning and to the development and exercise of higher-order thinking skills. But our experience has also shown us that in a large number of cases, the way concept mapping is used in the classroom does not lead to any of the two. In this paper we have discussed that the level of expertise of the students of concept mappers, together with the type of conditions concept mapping takes place can make a difference in whether the concept map is being used as a learning tool or not. Taking the time to help the students become Excellent Cmappers, and planning the concept mapping activities as a series of iterations with high-quality interventions can result in not only increased learning of both subject-matter content and higher-order thinking skills, but increased participation, interest and motivation on the part of the students.

References

Agarwal, P. K. (2018). Retrieval Practice & Bloom's Taxonomy: Do Students Need Fact Knowledge Before Higher Order Learning? *Journal of Educational Psychology. Advance Online Publication*. doi:10.1037/edu0000282

Anohina-Naumeca, A. (2015). Justifying the Usage of Concept Mapping as a Tool for the Formative Assessment of the Structural Knowledge of Engineering Students. *Knowledge Management & E-Learning, 7*(1), 56-72.

Bixler, G. M., Brown, A., Way, D., Ledford, C., & Mahan, J. D. (2015). Collaborative Concept Mapping and Critical Thinking in Fourth-Year Medical Students. *Clinical Pediatrics, 54*(9), 833-839. doi:10.1177/0009922815590223

Buldu, M., & Buldu, N. (2010). Concept Mapping as a Formative Assessment in College Classrooms: Measuring Usefulness and Student Satisfaction. *Procedia - Social and Behavioral Sciences, 2*(2), 2099-2104. doi:10.1016/j.sbspro.2010.03.288

Cañas, A. J., Hill, G., Carff, R., Suri, N., Lott, J., Eskridge, T., . . . Carvajal, R. (2004). CmapTools: A Knowledge Modeling and Sharing Environment. In A. J. Cañas, J. D. Novak, & F. M. González (Eds.), *Concept Maps: Theory, Methodology, Technology. Proceedings of the First International Conference on Concept Mapping* (Vol. I, pp. 125-133). Pamplona, Spain: Universidad Pública de Navarra.

Cañas, A. J., & Novak, J. D. (2006). Re-Examining The Foundations for Effective Use of Concept Maps. In A. J. Cañas & J. D. Novak (Eds.), *Concept Maps: Theory, Methodology, Technology. Proceedings of the Second International Conference on Concept Mapping* (Vol. 1, pp. 494-502). San Jose, Costa Rica: Universidad de Costa Rica.

Cañas, A. J., Novak, J. D., & Reiska, P. (2012). Freedom vs. Restriction of Content and Structure during Concept Mapping - Possibilities and Limitations for Construction and Assessment. In A. J. Cañas, J. D. Novak, & J. Vanhear (Eds.), *Concept Maps: Theory, Methodology, Technology - Proceedings of the Fifth International Conference on Concept Mapping* (Vol. 2, pp. 247-257). Valletta, Malta: University of Malta.

Cañas, A. J., Novak, J. D., & Reiska, P. (2015). How good is my concept map? Am I a good Cmapper? *Knowledge Management & E-Learning: An International Journal (KM&EL), 7*(1), 6-19.

Cañas, A. J., Reiska, P., & Möllits, A. (2017). Developing higher-order thinking skills with concept mapping: A case of pedagogic frailty. *Knowledge Management & E-Learning: An International Journal (KM&EL), 9*(3), 348-365.

Chiu, C.-H., Huang, C.-C., & Chang, W.-T. (2000). The Evaluation and Influence of Interaction in Network Supported Collaborative Concept Mapping. *Computers & Education, 34*(1), 17-25.

Correia, P., Cabral, G., & Aguiar, J. (2016). Cmaps with Errors: Why Not? Comparing Two Cmap-Based Assessment Tasks to Evaluate Conceptual Understanding. In A. J. Cañas, P. Reiska, & J. D. Novak (Eds.), (pp. 1-15): Springer, Cham.

De Simone, C., Schmid, R. F., & McEwen, L. A. (2001). Supporting the Learning Process with Collaborative Concept Mapping using Computer-based CommunicationTools and Processes. *Educational Research & Evaluation, 7*(2-3), 263-283.

Derbentseva, N., Safayeni, F., & Cañas, A. J. (2006a). Concept Maps: Experiments on Dynamic Thinking. *Journal of Research in Science Teaching, 44*(3).

Derbentseva, N., Safayeni, F., & Cañas, A. J. (2006b). Two Strategies for Encouraging Functional Relationships in Concept Maps. In A. J. Cañas & J. D. Novak (Eds.), *Concept Maps: Theory, Methodology, Technology. Proceedings of the Second International Conference on Concept Mapping* (Vol. 1, pp. 582-589). San Jose, Costa Rica: Universidad de Costa Rica.

Dowd, J. E., Duncan, T., & Reynolds, J. A. (2015). Concept Maps for improved Science Reasoning and Writing: Complexity isn't Everything. *ICBE-Life Sciences Education, 14*(4), ar39.

Fiedler, R. L., & Salas, E. *Concept Mapping: How To Help Learners Visualize Knowledge*. Retrieved from http://s3.amazonaws.com/publicationslist.org/data/fiedler/ref-11/fiedlersalasAECT.pdf

Jacobs-lawson, J. M., & Hershey, D. A. (2002). Concept Maps As an Assessment Tool in Psychology Courses. *Teaching of Psychology, 29*(1), 25-29.

Khodadady, E., & Ghanizadeh, A. (2011). The Impact of Concept Mapping on EFL Learners' Critical Thinking Ability. *English Language Teaching, 4*(4), 49-60. doi:10.5539/elt.v4n4p49

Kinchin, I. M. (2014). Concept Mapping as a Learning Tool in Higher Education: A Critical Analysis of Recent Reviews. *The Journal of Continuing Higher Education, 62*(1), 39-49.

Martínez, G., Pérez, Á. L., Suero, M. I., & Pardo, P. J. (2013). The Effectiveness of Concept Maps in Teaching Physics Concepts Applied to Engineering Education: Experimental Comparison of the Amount of Learning Achieved With and Without Concept Maps. *Journal of Science Education and Technology, 22*(2), 204-214. doi:10.1007/s10956-012-9386-8

Mason, C. L. (1992). Concept Mapping: A Tool to Develop Reflective Science Instruction. *Science Education, 76*(1), 51-63.

McClure, J. R., Sonak, B., & Suen, H. K. (1999). Concept Map Assessment of Classroom Learning: Reliability, Validity, and Logistical Practicality. *Journal of Research in Science Teaching, 36*(4), 475-492. doi:10.1002/(SICI)1098-2736(199904)36:4<475::AID-TEA5>3.0.CO;2-O

Miller, N. L., Cañas, A. J., Alves-Rosa, F., Ceballos, E., León, C., & Santana, D. (2010). Impacto de Retroalimentación Remota a Mapas Conceptuales Elaborados por Estudiantes del Proyecto Conéctate. In J. Sánchez, A. J. Cañas, & J. D. Novak (Eds.), *Concept Maps: Making Learning Meaningful, Proc. of the Fourth Int. Conference on Concept Mapping.* Viña del Mar, Chile: Universidad de Chile.

Moon, B., Johnston, C., & Moon, S. (2018). *A Case for the Superiority of Concept Mapping-Based Assessments for Assessing Mental Models.* In: A. J. Cañas, P. Reiska, C. Zea & J. D. Novak (Eds), *Concept Mapping: Renewing Learning and Thinking. Proceedings of the 8th Int. Conference on Concept Mapping*, Medellín, Colombia: Universidad EAFIT.

Mullis, I. V. S., & Martin, M. O. (Eds.). (2013). *TIMSS 2015 Assessment Frameworks*: TIMSS & PIRLS International Study Center.

Novak, J. D., & Cañas, A. J. (2004). Building on Constructivist Ideas and CmapTools to Create a New Model for Education. In A. J. Cañas, J. D. Novak, & F. M. González (Eds.), *Concept Maps: Theory, Methodology, Technology. Proceedings of the 1st International Conference on Concept Mapping*. Pamplona, Spain: Universidad Pública de Navarra.

Novak, J. D., & Cañas, A. J. (2008). *The Theory Underlying Concept Maps and How to Construct and Use Them* (IHMC CmapTools 2006-01 Rev 01-2008). Retrieved from Institute for Human and Machine Cognition (IHMC): https://cmap.ihmc.us/docs/theory-of-concept-maps

Novak, J. D., & Gowin, D. B. (1984). *Learning How to Learn*. New York, NY: Cambridge University Press.

Pérez Rodríguez, A. L., Suero López, M. I., Pardo Fernández, P. J., & Montanero Fernández, M. (2006). Utilización de Mapas Conceptuales para Mejorar los Conocimientos Relativos a la Corriente Eléctrica Continua mediante su "Reconstrucción Colaborativa" In A. J. Cañas & J. D. Novak (Eds.), *Concept Maps: Theory, Methodology, Technology: Proc. of the Second Int. Conference on Concept Mapping.* San José, Costa Rica: Universidad de Costa Rica.

Rebich, S., & Gautier, C. (2005). Concept Mapping to Reveal Prior Knowledge and Conceptual Change in a Mock Summit Course on Global Climate Change. *Journal of Geoscience Education, 53*(4), 355-365.

Reiska, P., Soika, K., & Cañas, A. J. (2018). Using Concept Mapping to Measure Changes in Interdisciplinary Learning during High School. *Knowledge* Management *& E-Learning, 10*(1), 1-24.

Robinson, W. R. (1999). A View from the Science Education Research Literature: Concept Map Assessment of Classroom Learning. *Journal of Chemical Education, 76*(9), 1179.

Ruiz-Primo, M. A. (2004). Examining Concept Maps as an Assessment Tool. In: *Concept Maps: Theory, Methodology, Technology. Proc. of the First Int. Conference on Concept Mapping.* Universidad Pública de Navarra, Pamplona, Spain, pp. 555-563

Ruiz-Primo, M. A., Shavelson, R. J., Li, M., & Schultz, S. E. (2001). On the Validity of Cognitive Interpretations of Scores from Alternative Concept-Mapping Techniques. *Educational Assessment, 7*(2), 99-141.

Safayeni, F., Derbentseva, N., & Cañas, A. J. (2005). A Theoretical Note on Concept Maps and the Need for Cyclic Concept Maps. *Journal of Research in Science Teaching, 42*(7), 741-766.

Schau, C., Mattern, N., Zeilik, M., Teague, K. W., & Weber, R. (2001). Select-and-Fill-In Concept Map Scores as a Measure of Students' Connected Understanding of Science. *Educational and Psychological Measurement, 61*(1), 136-158.

Soika, K., Reiska, P., & Mikse, R. (2012). Concept Mapping as an Assessment Tool in Science Education. In A. J. Cañas, J. D. Novak, & J. Vanhear (Eds.), *Concept Maps: Theory, Methodology, Technology. Proceedings of the Fifth International Conference on Concept Mapping* (Vol. 1, pp. 127-134). Valletta, Malta: University of Malta.

Soleimani, H., & Nabizadeh, F. (2012). The Effect of Learner Constructed, Fill in the Map Concept Map Technique, and Summarizing Strategy on Iranian Pre-University Students' Reading Comprehension. *English Language Teaching, 5*(9), 78-87. doi:10.5539/elt.v5n9p78

Stoddart, T., Abrams, R., Gasper, E., & Canaday, D. (2000). Concept Maps as Assessment in Science Inquiry Learning--A Report of Methodology. *International Journal of Science Education, 22*(12), 1221-1246.

Strautmane, M. (2012). Concept Map-Based Knowledge Assessment Tasks and their Scoring Criteria: An Overview. In A. J. Cañas, J. D. Novak, & J. Vanhear (Eds.), *Concept Maps: Theory, Methodology, Technology. Proceedings of the Fifth International Conference on Concept Mapping* (Vol. 2, pp. 80-88). Valletta, Malta: University of Malta.

Tricot, A., & Sweller, J. (2014). Domain-Specific Knowledge and Why Teaching Generic Skills Does Not Work. *Educ Pychol Review, 26*, 265-283. doi:10.1007/s10648-013-9243-1

Walker, J. M. T., & King, P. H. (2003). Concept Mapping as a Form of Student Assessment and Instruction in the Domain of Bioengineering. *Journal of Engineering Education, 19*(2), 167-179.

Wei, W., & Yue, K.-B. (2016). Using Concept Maps to Teach and Assess Critical Thinking in IS Education.