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Using Concept Maps to Create Meaningful Learning in Medical Education

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Abstract

After defining concept maps, we will present the historical development and theoretical foundations of concept maps derived from disciplines outside of medical education. With this foundation and based on the scoping review conducted, the major focus of this article will shift to the application of concept mapping in medical education. We have selected instructional strategies and sample maps for three contemporary challenges facing medical education to illustrate the portability and broad application of concept maps: 1. linking basic sciences and clinical practice, 2. developing clinical reasoning, and, 3. interprofessional and group learning. Finally, future research studies in concept mapping are suggested.

Introduction

The purpose of this article is to provide an in-depth discussion of concept mapping as a meaningful learning strategy in medical education. Figure 1 presents the major areas addressed in this article, including the theoretical foundations, along with the applications in medical education in the form of a concept map.
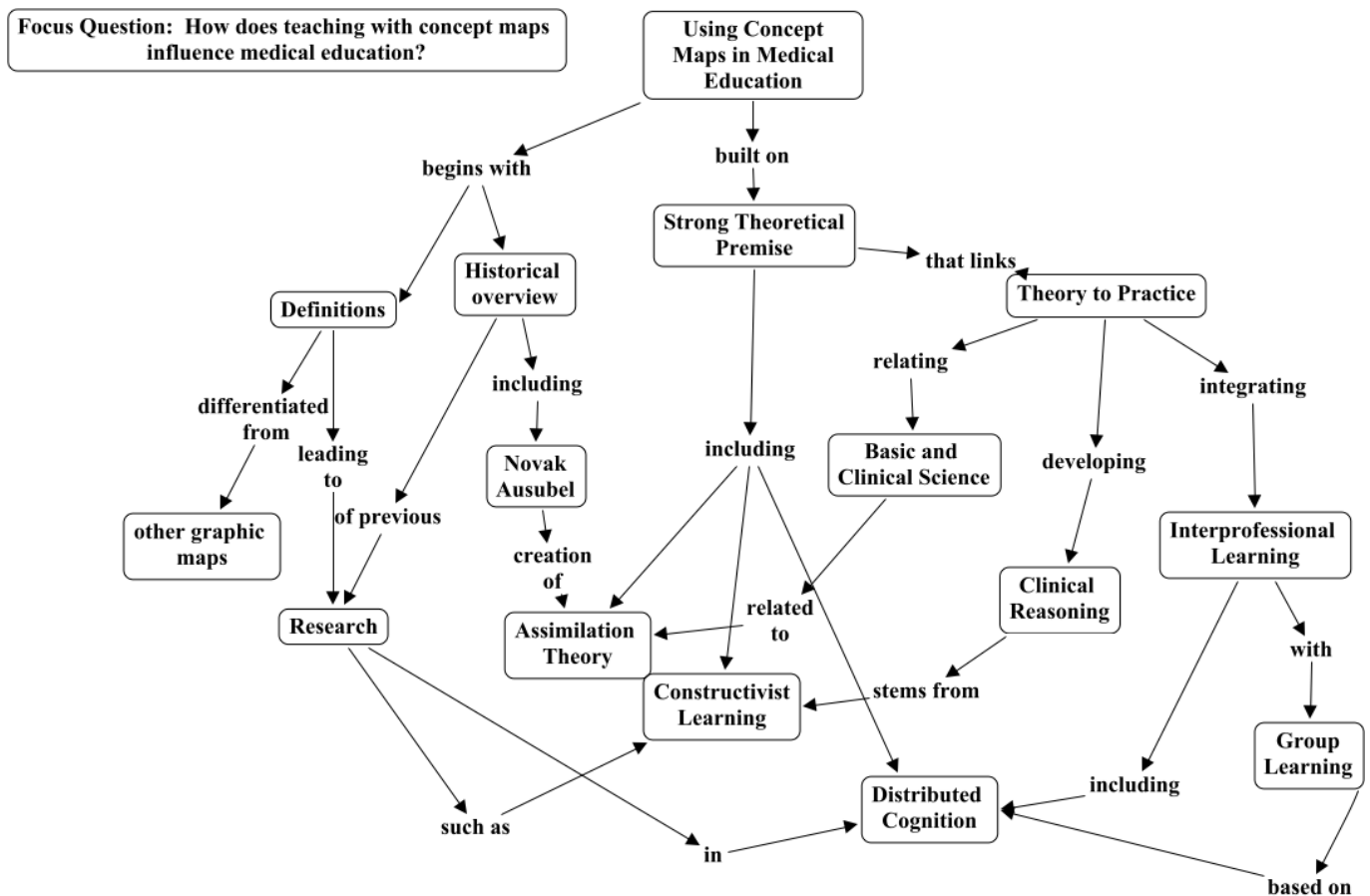
Figure 1: Concept Maps in Medical Education

The ultimate reason for promoting meaningful learning in medical education is to foster the development of reflective physicians who are prepared to provide optimal patient care in clinical practice. Learning in a meaningful way means that medical students, residents, and practicing physicians actively seek out ways to link new information and experience with what they already know, thus creating an organized knowledge base leading to the development of adaptive expertise in medical practice. Concept mapping, a teaching and learning strategy developed by Novak and Gowin (1984) is one strategy to promote meaningful learning. Concept maps are a strategy that focuses on creating linkages across bodies of knowledge and linking theory to practice. Concept maps are based on the work of David Ausubel (1963, 2000) and have been used in education for over 30 years. Through our expertise on this subject and a scoping review, we identified a vast body of literature supporting the use of concept maps in facilitating learning across age groups, professional disciplines, and educational contexts (Cañas, Coffey, Carnot, Feltovich, Hoffman, Feltovich, & Novak, 2003; Novak & Cañas, 2006a).

Concept Maps: What are they? According to Novak and Gowin (1984), a concept map (see Figure 2) is "a schematic device for representing a set of concept meanings in a framework of propositions" (pg. 15). In this view, the student thinks and learns with concepts by linking and chunking new concepts to what they already know. In addition, our contemporary understanding of memory suggests that concepts are stored hierarchically and differentiated as learning grows. This learning with concept maps means that one is making an intentional effort to link, differentiate and relate concepts to each other in a hierarchical fashion.

Ausubel (2000) and Ausubel, Novak and Hanesian (1986) believe that thinking and learning with concepts uses three processes, *subsumption, progressive differentiation* and *integrative reconciliation.* During *subsumption* lower order concepts are incorporated under higher order concepts. This process of subsumption leads to the creation of a

hierarchy of knowledge structures and understanding. Even though this may be difficult to evaluate in educational settings it is essential to learning. For example, in Figure 2 the concept of effective learning is subsumed under the concept of organized knowledge. In the *progressive differentiation* process, concepts are broken down into finer and finer components. In this way, progressive differentiation is similar to an analysis process, meaning that the concepts are separated into their elemental components. In Figure 2, note how the concept of hierarchically structured is differentiated into three concepts, creativity, experts and cognitive structures. Finally, *integrative reconciliation* is a process where the learner attempts to reconcile and link together concepts from the left side of the map to those on the right side of the map. This is similar to a synthesis process, meaning that concepts are connected in unique ways to form a complex whole. For example, at the bottom of Figure 2 note how the concept of creativity is linked to interrelationships.

Figure 2, a concept map of a concept map, depicts these three processes. In looking at this map, one can see how the lower order concepts are subsumed under higher order concepts, how concepts are differentiated, and how concepts are horizontally reconciled. Integrative reconciliation is demonstrated by the horizontal links on the map.
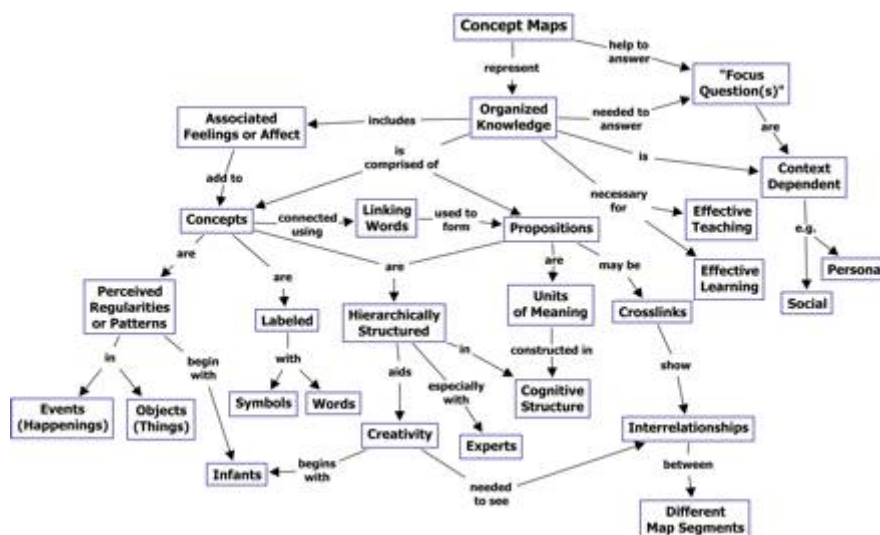

Figure 2: Concept map showing key features of concept maps (Novak & Cañas, 2006a, pg. 2).

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To create a concept map the learner engages in an active process that uses these three ideas (Daley, 2010). First, the leaner identifies the most general concepts and places them at the top of the map. Second, the learner identifies specific concepts that relate to the general concepts in some fashion (*subsumption*). Third, the learner ties together the general and specific concepts with linking words that make sense to them (*progressive differentiation*). Finally, the learner actively looks for cross-linkages that tie concepts from one side of the map to the other (*integrative reconciliation*).

Choosing linking words is one of the most difficult and yet, most important parts of creating a concept map. Whatever linking words the learner chooses will change the relationship between the concepts and thus the meaning portrayed on the map. Linking words are also the major feature that differentiates concept maps from other forms of mapping. Mind maps, conceptual diagrams and visual metaphors are all graphic organizers used in note taking,

understanding the development of characters in a novel, or brainstorming (Eppler, 2006). Yet, these strategies focus on pointing out that a relationship between two concepts exists, but they usually do not use linking words to define the nature of the relationship.

Why are concept maps applicable in medical education? In medical education, part of what one needs to learn is how to deal with vast amounts of information so that the information is actually usable and applicable when providing care to patients. Committing information to memory is one skill. However, medical students typically need additional abilities to function in clinical practice. These include, first, being able to integrate and connect various pieces of information that pertain to a clinical case (developing understanding), and, second, the student needs to decide the best course to take based on that information (taking action). Creating a networked, organized knowledge base and being able to draw on that knowledge base for making clinical decisions is a hallmark of expert performance. Kinchin, Cabot, and Hay (2008) help us understand how expert performance entails moving elegantly between understanding and action in the clinical arena. As is evident in this work (Hay & Kinchin, 2006) concept maps provide a strategy for navigating these different thought processes. In this way, the maps can assist in helping students link basic science to clinical practice and in promoting clinical reasoning.

Additionally, concept maps are applicable in medical education because they help make student and practitioner thought processes more visible and specific. Furthermore, the maps can provide a vehicle by which groups of learners can share their thinking and understanding on particular cases or topics. Finally, maps can specify different and/or complementary roles of various health care providers within an interdisciplinary team. Concept maps can provide a method for team member to understand the connections and overlap in their roles. The maps also provide a way to differentiate one person's role from another.

Concept Map Development: What are the origins of concept mapping?

Dr. Joe Novak created concept maps in 1972 as part of a research program at Cornell University where he sought to understand the changes in children's knowledge of science (Novak & Musonda, 1991). The science lessons had been constructed based on Ausubel's (1968) assimilation theory of learning. The three processes of subsumption, progressive differentiation, and integrative reconciliation, outlined earlier, are part of this theory thus, the researchers were looking for ways to assess and evaluate changing knowledge structures. During the early years of this work a number of different techniques were incorporated in the evaluation, including photographs, multiple choice tests, and line drawings. The researchers determined that the clinical interview was the best way to assess conceptual change. As Novak and Musonda (1991) indicate, "Concept mapping as we have developed and employed it differs from most other knowledge representation schemes in that it utilizes ideas from constructivist epistemology and Ausubel's (1968, 1986) assimilation theory of cognitive learning" (p. 125). Since that time, concept maps have been used in a variety of contexts including: a teaching and learning strategy, a curriculum development tool, a strategy to assess learning and a tool to capture knowledge structures. This broad applicability crosses disciplinary and age boundaries.

Methods

The purpose of this scoping review was to synthesize concept mapping literature and determine ways in which the

maps could be integrated into teaching and learning in medical education. We used a scoping review methodology to supplement the expertise of the authors in this field. Scoping reviews identified by May, Roberts and Popay (2001) tend to map the key concepts of a research area along with the types of evidence available. Scoping reviews may be stand-alone projects and differ from a systematic review in that they address broader topics and are less likely to focus on a specific research question (Arksey & O'Malley, 2005; Dijkers, 2015) According to Davis, Drey and Gould (2009) "scoping involves the synthesis and analysis of a wide range of research and non-research material to provide greater conceptual clarity about a specific topic or field of evidence" (p. 1386).

For this scoping review, manuscripts were identified, reviewed, and discussed by the authors leading to the development of the three themes presented in this paper. Our search terms (concept maps, concept mapping, Cmaps, knowledge modeling, assimilation theory, constructivism, distributed cognition) were developed by the authors following an initial review of literature and our own work on the topic. Concept mapping literature was reviewed in the discipline of education; including K-12 education, higher education, nursing education and medical education. We included studies of all designs (qualitative, quantitative, and mixed-methods), and we included essays along with descriptive articles of educational interventions. We did not use methodological quality criteria in the study selection. We believe that the scoping methodology was an appropriate approach given that the purpose of this review was to map this research, to explicate the theoretical underpinnings of concept maps and to identify three areas in which concept mapping could be applied in teaching and learning within medical education.

Research Summary

There is a vast body of literature on concept mapping in K-12 education, higher education and now emerging in medical education. In summary, concept mapping research conducted over the last 30 years establishes that concept maps are a successful strategy to foster meaningful learning in a wide variety of contexts and within various disciplines (see: http://cmc.ihmc.us/). Maps have been used and continue to be used across the education spectrum from elementary to graduate school. Research indicated that the maps are effective in **fostering meaningful learning** (Al-Kunifreed & Wandersee, 1990; Garcia, 2010; Novak & Gowin, 1984; Novak & Wandersee, 1990; Silesky & Badilla, 2008; Tarte, 2006), **assessing learning** (Fischler, et al., 2002; McGaghie, McCrimmon, Thompson, Ravitch, & Mitchell, 2000; Reiska, 2005; West, Pomeroy, Park, Gerstenberger, & Sandoval, 2000; West, Park, Pomeroy & Sandoval, 2002), **promoting curriculum development** (Bowen & Meyer, 2008; Edmondson, 1995; Heinze-Fry & Ludwig, 2006; Riesco, Fondón, Alvarez, 2008), **developing instructional strategy** (Fonseca, Extremina, & Fonseca, 2004, Prabhu, Elmesky, & Czarnocha, 2006, Stoddart, 2006) and **teaching specific content.** Teaching specific content has been researched in areas such as **business**, where concept maps were used to teach strategic intent (Fourie & Westhuizen, 2008), entrepreneurial behavior (Kyrö, Seikkula-Leino & Mylläri, 2008), and business planning (Kyrö & Niskanen, 2008). Concept maps have also been researched **engineering** (Feregrino-Hernández, Reza-García, Ortiz-Esquivel, Navarro-Clemente, & Domínguez-Pérez, 2006), **math** (Heinze-Fry, 2004; Oneca, Sanzol, & Poveda, 2006; Vagliardo, 2004), **physics** (Alias & Tukiran, 2006; Valadares, Fonseca, & Soares, 2004); **photography** (Gimena, 2004), **writing** (Straubel, 2006), **pharmacy** (Hill, 2006), **nursing education** (Daley, et al., 1999), and **medical education** (Illas, 2006; Torre, Daley, Stark-Schweitzer, Siddartha, Petkova, & Ziebert, 2007; Torre, During, & Daley, 2013). In addition, Daley, Conceição, Mina, Altman, Baldor and Brown (2010) found in an analysis of over 300 manuscripts presented at the International Concept Mapping Conferences that conference research in concept mapping had been conducted in six overall thematic areas; a. teaching and learning, b. assessment and scoring, c. knowledge development, d. software development, e. professional development, and, f. research methods.

In the 1990s, the use of concept mapping continued to expand as technology made the map construction process

seamless and revision simpler. As a result of US federal funding, the Institute of Human and Machine Cognition (IHMC) developed the software program Cmap Tools (See: http://cmap.ihmc.us/products/). Cmap tools is a free software program that allows concept maps to be created on desktops, laptops or Ipads. As technology fostered the ease of concept map development the use of the tool across groups, organizations and in countries around the world increased.

The 2000s have seen the growth of mapping in other areas as seen by the variety of topics presented at the Concept Mapping Conferences (see: http://cmc.ihmc.us/). The use of concept maps in knowledge management (Coffey & Hoffman, 2003; Coffey, Eskridge, & Sanchez, 2004) has shown that maps are an effective tool for capturing and archiving knowledge. Additionally, maps have been used to organize and navigate through large volumes of information.

Finally, Daley & Torre (2010) in a literature review of concept mapping in medical education demonstrate that maps have been used in medical education to promote meaningful learning, to provide additional resources for learning, to assist instructors in providing feedback to students and to conduct assessment of learning and performance. Based on the literature review, Daley & Torre state, "the research cited in this review demonstrates that concept maps can assist in medical student learning. Additionally, for teaching staff in medical schools, this review provides ideas on how to use concept maps to foster critical thinking and clinical reasoning in medical students, how to incorporate concept mapping within PBL (problem base learning) approaches, and how to use concept mapping in group and collaborative learning" (2010, p. 44). Concept maps have also been successfully used in medical education for teaching evidence-based practice (Saeidifard, Heidari, Foroughi, & Soltani, 2014), and within a team based learning exercise (Knollmann-Ritschel & Durning, 2015). As Knollmann-Ritschel & Durning state when discussing their use of concept maps in a team based learning exercise, "Our findings suggest concept maps can provide a unique means of determining assessment of learning and generating feedback to students. Concept maps can also demonstrate knowledge acquisition, organization of prior and new knowledge, and synthesis of that knowledge across disciplines in a unique way providing an additional means of assessment in addition to traditional multiple-choice questions" (2015, p. 64).

Theoretical Underpinnings

The scoping literature review conducted for this article, demonstrated that the development and use of concept maps is grounded in assimilation theory, constructivist learning and distributed cognition. Each of these theoretical perspectives is explored here.

Assimilation Theory. Assimilation theory was created by Ausubel (1968) as part of a cognitive approach to understanding learning. In this work, Ausubel makes a crucial distinction between meaningful and rote learning. Meaningful learning occurs when new learning can be related to previous knowledge. Ausubel indicates that one of the most important ideas in meaningful learning is to understand what the learner already knows and to teach accordingly. Linking new learning to previous understanding is what makes learning meaningful. Rote learning, on the other hand, is based on memory and is not linked to a pre-existing cognitive framework. Rote learning often remains isolated, thus making it more difficult for the learner to connect this new learning in ways that will be useful and applicable in future situations.

The principle of assimilation is a key feature in Ausubel's (1968) concept of meaningful learning. Assimilation is intended as part of the process where a new potentially meaningful idea is "related to and assimilated by an established idea" (1968, p. 91) resulting in an interaction and meaningful product. In other words, the term

assimilation "is the hypothesized tendency for the new meaning to be 'reduced' to the meaning of the more established idea" (p. 91). Torre and Daley (2013) explain that theoretically assimilation is important for two reasons: first, the creation and retention of meaningfully learned concepts, and second, the organization of new knowledge structures. So not only are concepts assimilated into the learners' cognitive structures, but this assimilation continues until new knowledge structures are created as a result.

In developing this theoretical framework, Ausubel (1968) described three types of meaningful learning: representational learning, propositional learning and concept learning. Representational learning "concerns the meaning of unitary symbols or words" (1968, p. 43) and what they represent. Propositional leaning involves the learning of "new ideas expressed in propositional form" (p. 43). Thus, in propositional learning the purpose is to learn "the meaning of verbal propositions that express ideas" (p. 43) where the propositions are created by combining or relating individual words to each other. In concept learning, words that are related to form propositions actually constitute concepts, hence "propositional learning largely involves learning the meaning of a composite idea generated by combining into sentences single words each of which represents a concept" (p. 43).

Finally, learning in a meaningful way involves the development of meaningful relationships among concepts, thus resulting in the creation of "well integrated, highly cohesive knowledge structures that enable them to engage in the type of inferential and analogical reasoning required for success in the natural sciences" (Mintzes, Wandersee, & Novak, 1998, p. 41).

Novak and Gowin (1984) have incorporated elements of the meaningful learning principles of Ausubel (1968) into their work on concept mapping. In particular, concept mapping facilitates the student's ability to organize information, assess existing knowledge gains, develop insights into new and existing knowledge and transfer knowledge to new experiences. Also, evident from Ausubel's work, and used in concept mapping, is the opportunity to link new knowledge with previous knowledge, ultimately to not only create meaningful learning, but to contribute to the transfer of knowledge to future problems. From a student's perspective, concept mapping encourages them to think independently, produces more self-confidence and provides an increased awareness of making connections across different bodies of knowledge.

Constructivist Learning. Human constructivism is grounded in a number of important assumptions: first, human beings are creators of meaning, thus individuals construct meaning by making connections between new concepts and those that are part of a pre-existing knowledge framework. Constructivist knowledge, in this view, is an organized framework of meaningfully related concepts constructed by the learner. Second, teachers are facilitators of meaning making activities and conceptual change. Interaction, reflection and active participation are learning activities that can be fostered by teachers to create meaning, sharing and meaningful learning. Third, learners are seen as independent, meaning making individuals capable of restructuring knowledge by creating new relationships among concepts when supported by an environment that favors conceptual change and integration of concepts.

Constructivism "is a model of how learning takes place" (Cobern, 1993, p. 105) and a foundation for a variety of educational research projects. Constructivism can be applicable to many learning situations and its theoretical underpinnings make it particularly suitable for practical applications in medical education. According to Cobern (1993), in looking through a constructivist lens, it becomes apparent that "knowledge is a meaningful interpretation of our experience of reality" (Cobern, 1993, p. 109). Moreover, if knowledge is generated from meaningful interpretation, then "the learning of knowledge must also involve meaningful interpretation" (p. 109). Therefore, learning does not occur by transmission from teacher to student, but by making sense of what learners' experience. In a constructivist approach, "the student is always an active agent in the process of meaningful learning" (p. 110)

where learning occurs by interpretation and is influenced by prior knowledge. Furthermore, learning is facilitated by inquiry activities that foster discourse, and allow learners to engage in cooperative learning and interpretation of ideas.

Constructivism has become an important alternative to traditional educational practices in which "learning has been viewed as essentially a matter of storing information for later recall" (Iran-Nejad, 2001, p.17). Constructivism in the classroom is characterized by a change in the role played by the students who "instead of the teacher, organize information, explore the learning environment, conduct learning activities, and monitor their own learning" (p. 18). The teacher assumes a supporting or reflective role while students engage in meaningful learning and critical thinking. Thus, for the teacher, constructivism means becoming a reflective practitioner whose main goal is to create the proper setting and environment "for students to construct knowledge for themselves" (p. 27). This involves using questions and student-centered activities rather than providing answers so that students thinking and further exploration are encouraged. When considering the role of memory and constructivist learning, Iran-Nejad (2001) states that "if memory occurs in constructivism, it is because it is constructed for some internal, personal reasons" (p. 23). In other words, "memorizing the words of the teacher or the knowledge that others have created is often not productive because knowledge is not a ready-made, transferable product but, rather, a product of the learner's thinking created in a multisource context" (Iran-Nejad, 2001, p.23).

Concept mapping is also an important application of a constructivist approach. As a resource for learning, concept maps allow the student to demonstrate their mastery of the concepts associated within a particular body of knowledge (Marchand, D'Ivernois, Assal, Slama, & Hivon, 2002). Concept mapping is a creative activity that fosters reflection into one's own understanding (Coffey, Carnot, Feltovich, Hoffmann, & Cañas, 2003). According to Pinto and Zeitz (1997), concept maps can facilitate students' understanding of the organization and integration of important concepts. By connecting old and new knowledge, this type of learning clarifies knowledge, improves critical thinking and assists in completing missing knowledge (Harpaz, Balik, & Ehrenfeld, 2004).

Distributed Cognition. In recent years, Hallon, et al. (2000) and Hutchins (1995a, 1995b) have engaged in the study of cognition from a new perspective. These scientists/researchers have advanced the idea that cognition is not only located in the mind of an individual but that it is distributed across groups of individuals. Distributed cognition, as a theory, (D-Cog) advances the idea that the organization of the mind is both internal and external. Thus, there is a social, interpersonal and cultural aspect to cognition. As Lave indicates,

> There is a reason to suspect that what we call cognition is in fact a complex social phenomenon. The point is not so much that arrangements of knowledge in the head correspond in a complicated way to the social world outside the head, but that they are socially organized in such a fashion as to be indivisible. 'Cognition' observed in everyday practice is distributed—stretched over, not divided among—mind, body, activity and culturally organized settings, which include other actors (Lave 1988, p. 1).

Hallon et al. (2000) indicate that D-Cog, as any cognitive theory seeks to understand the organization of cognitive systems. However, unlike traditional theories D-Cog extends the understanding of cognition beyond the individual to interactions between individuals, as well as, interactions between the individual and the environment. In this view, D-Cog looks for cognitive process wherever they may occur along with the relationships that participate in the cognitive process.

Based on this work, Hallon and Hutchins suggest three ways in which cognition may be distributed (Hallon et al. 2000, p. 176).

1. Cognitive processes may be distributed across the members of a social group.

2. Cognitive processes may involve coordination between internal and external (material or environmental) structure.

3. Processes may be distributed through time in such a way that the products of earlier events can transform the nature of later events.

There have been numerous studies researching how D-Cog is applied in a variety of professions and workplaces. For example, distributed cognition has been studied in sports teams (Williamson & Cox, 2014). In their work, Williamson & Cox (2014) differentiate between a team of individual experts and an expert team. They indicate that in an expert team "people are considered to be cognitively interdependent, relying on each other for aspects of their own individual cognitive process and completing tasks by sharing representations and acting together in idiosyncratic ways" (p. 642). Expert teams have knowledge of the game and knowledge of their own skills, but they differ from teams of individual experts in that they also have explicit and implicit knowledge of others skills and they may have skills that are transformed by others.

Adding to our understanding of D-Cog, Pimmer, Pachler, & Genewein (2013) have applied this theoretical framework to the clinical workplace. They use an empirical example to demonstrate how cognition is distributed among a medical student, resident and attending physician. They demonstrate how cognition is embedded in interwoven representations, co-constructed representations, redundant representations, intersubjective representations, and substantiated representations. Berndt, Furniss, Blandford (2014) then applied D-Cog to the study of the use of infusion devices in the operating room.

Finally, Gilardi, Guglielmetti & Pravettoni (2014) conducted an exploratory ethnographic study in two emergency departments. Using a distributed cognition framework, they collected observation and interview data over a four-month period. They identified a specific distribution of cognitive work between physicians and nurses that improved the quality of care, yet, crossed interprofessional boundaries. They recommend practice based training aimed at developing a deep understanding of team cognition and professional roles.

As has been demonstrated, distributed cognition encompasses a social, interpersonal and cultural component to cognition that expands our understanding of cognition and learning beyond its traditional boundaries. Concept mapping is a tool that can assist teams and groups in understanding how distributed cognition works and how this theoretical premise can facilitate group work along with interprofessional work. Concept maps can be created both individually and in a collaborative fashion. Sánchez and FitzGibbon (2005) analyzed students' individual and group concept maps using a distributed cognition framework. They found that the individual maps allowed the students to create an "object to think with" (p. 1100) and when in groups the concept map became a resource of distributed information thus facilitating a process of collaborative distributed cognition.

In summary, as indicated in Figure 3, the three theoretical premises of assimilation theory, constructivist learning and distributed cognition frame our understanding of concept mapping and its use in both individual and group learning. Figure 3 indicates that even through there are differences in these three theoretical underpinning each focuses on the creation of meaning. Individual and/or group concept mapping can be used as learning strategies to foster the development of meaning in medical education.
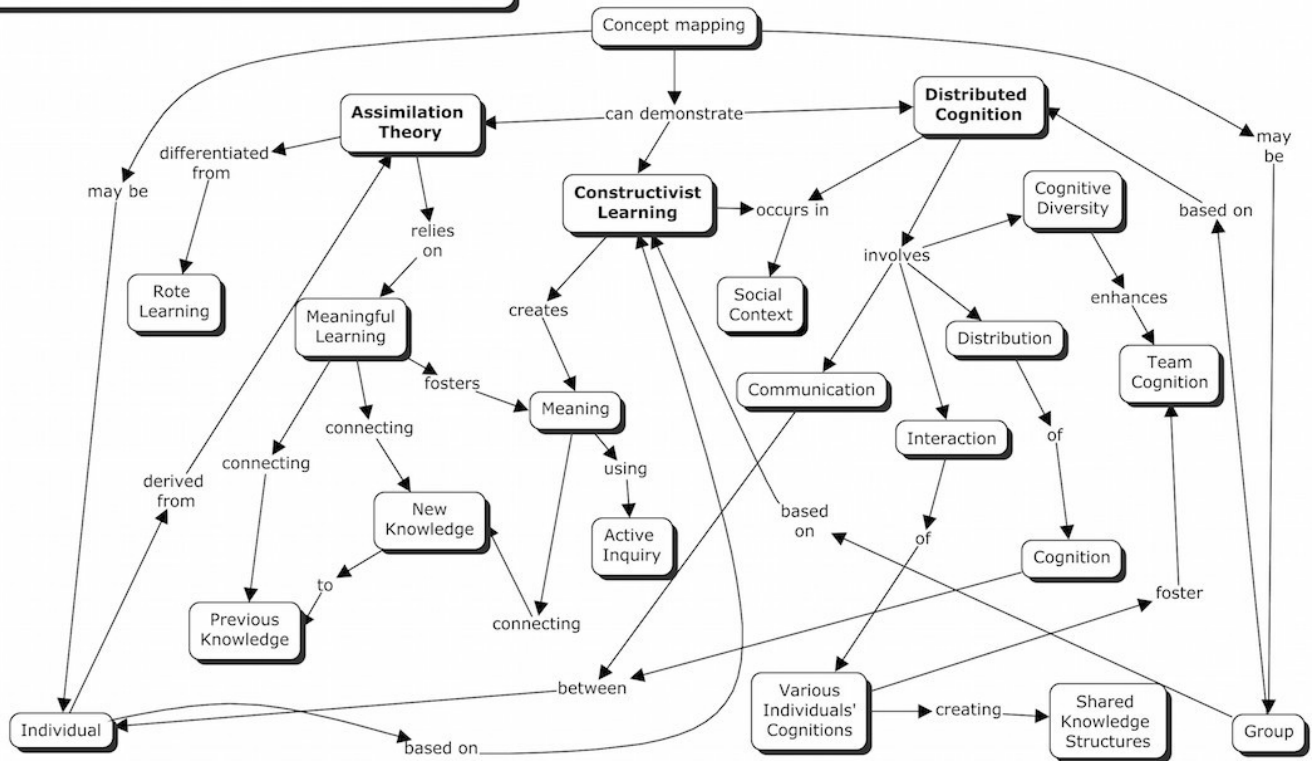
Figure 3: Theoretical Underpinnings of Concept Mapping

Linking Theory to Practice: What Works?

The next section of this article presents ideas for using concept maps in medical education. These examples demonstrate how concept maps can facilitate linking basic and clinical science, developing clinical reasoning and fostering interprofessional group work and learning. These examples demonstrate how the underlying theoretical premises discussed inform the use of concept maps in medical education.

Linking Basic Science and Clinical. Concept maps, in medical education have been used to develop the knowledge structures of students in the basic sciences, as well as, in the clinical sciences (Edmondson & Smith, 1998; Gonzales, et al. 2008; McGaghie, et al., 2000; West et al. 2000). The integration of basic and clinical sciences happens in two main areas, curriculum development and instructional design.

Concept maps can be a visual representation of course and curriculum materials. This visual representation helps render these materials accessible to teachers, administrators and students. As such, the maps can be a useful tool to ensure alignment of the overall curriculum, learning outcomes and specific course content. Additionally, concept maps allow teachers to determine what learning material needs more or less emphasis. The use of concept mapping can also be a tool to tie learning assessment to curricular elements and to create interdisciplinary activities that integrate multiple concepts from different courses (McDaniel, Roth, & Miller, 2005).

In the process of curriculum development, the collaborative efforts of a group of basic scientists and clinician educators can lead to the creation of a series of concept maps that allow a meaningful visual representation of vertical and horizontal curriculum threads. The use of linking words and horizontal cross-links among concepts can clarify the relatedness of topics across knowledge domains. In addition, the relationships among the most important

and pivotal concepts in the curriculum can then be made visible. As such, an integrated network of concept maps can serve to guide curriculum development, foster curriculum revisions, monitor curriculum implementation and facilitate the change process where needed. A networked series of concept maps can serve as representation of the entire curriculum and easily show emerging threads or pathways.

Because concept mapping requires the identification and prioritization of key concepts, the construction of concept maps can help medical school faculty determine major areas of emphasis across specialties. At the same time, this process helps suggest new relationships among topics and disciplines. Furthermore, concept maps can provide teachers and instructors (in the basic and clinical sciences) with a tool to see relationships outside the boundary of a discipline, thus facilitating the integration process (Edmonson, 1995). In addition, by creating consecutive revisions of the maps, teachers can see where to make changes within the curriculum across time. Adding or deleting maps provides an opportunity for clarification of concepts, thus ensuring a cohesive and dynamic curriculum development process (Star & Krajcik, 1990). Concept maps also allow curriculum developers to ensure that all content has been addressed and that key concepts have not been inadvertently deleted.

In addition, concept maps can assist in the curriculum mapping process. The curriculum mapping process, provides a picture of the curriculum and demonstrates how content, outcomes, assessments and learning activities are connected and integrated (Harden, 2001). We are aware that the use of curriculum mapping is an effective tool for curriculum design (Willett, 2008). We are not suggesting it should be replaced by the use of concept mapping nor that one method is superior to the other. They are different tools that can coexist, increasing the strength of both. Concept maps allow educators, within a curriculum mapping process, to develop a more granular construction of an integrated network of learning units, delve more deeply into each area and tie assessments effectively to educational activities and goals. Further research is needed to explore the integration of concept mapping and curriculum mapping. The strength of this research would lie in developing an understanding of how one strategy can help the other create, explain and revise basic and clinical science concepts and their connections.

Concept maps can also be a valuable tool to integrate basic and clinical sciences in the instructional design process. As seen in Figure 4, concepts from clinical medicine, anatomy, histology and microbiology can be integrated around a disease process. This kind of map may greatly facilitate the process of collaboration in instructional course design (Cristea & Okamoto, 2001).
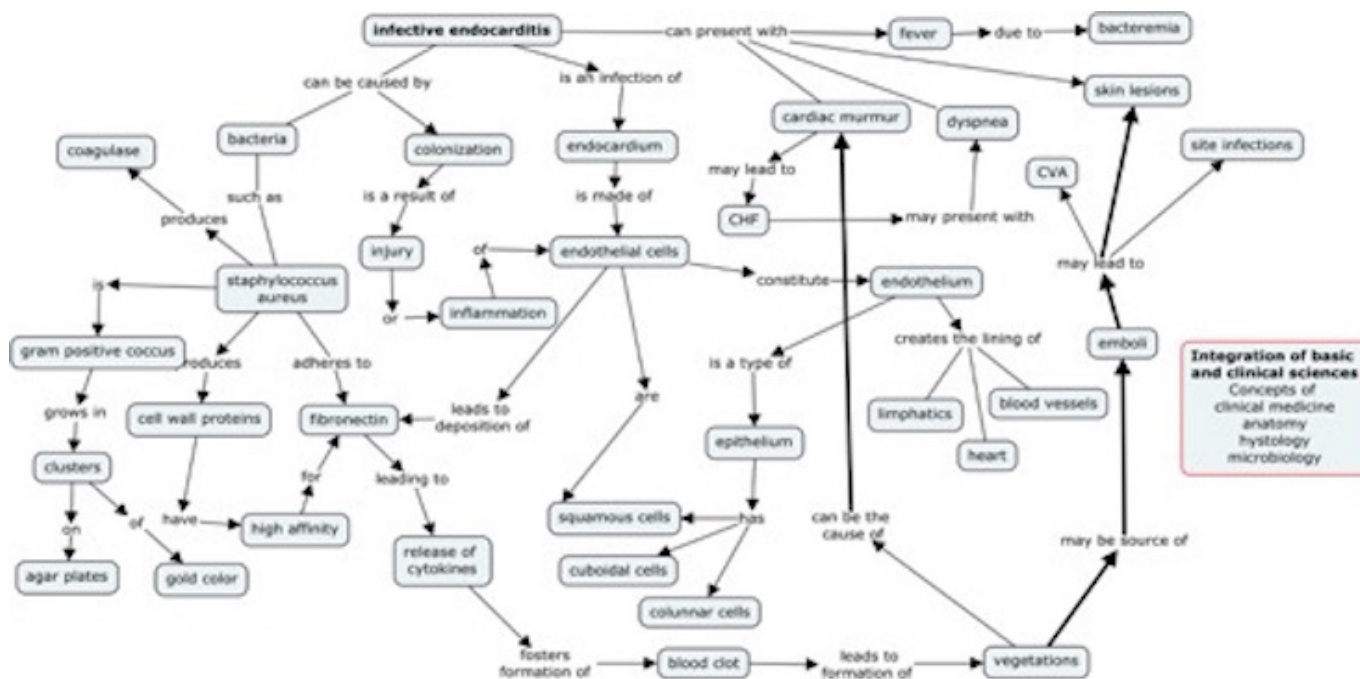
Figure 4: Concept Map Showing Integration of Basic and Clinical Sciences

Concept mapping has also enhanced the understanding of pathophysiology within a problem based learning (PBL) course for medical students. This PBL course included clinical cases such as hypertension, coronary artery disease and heart failure (Rendas, Fonseca, & Pinto, 2006). Students indicated that concept maps provided a useful visualization of concepts, promoted meaningful learning and allowed them to revise and review material before final examinations. However, students also reported that this strategy was time consuming. In addition, Veronese et al (2013) demonstrated that using concept maps in PBL enhanced student performance in a first-year physiology course.

Research by Vink et al (2015) documented that concept mapping facilitated the integration of basic and clinical sciences concepts in the co-construction of concept maps relevant to medical students. A group of expert physicians, in basic and clinical science, and a group of residents developed a series of concept maps that included all the relevant concepts and relationships needed by medical students to understand eight different clinical problems. Physicians, in this study, perceived concept mapping as an enjoyable tool that fostered cooperative learning and provided unique opportunities for interactions, particularly when there was a need for joint decisions. Residents found maps to be a useful way to learn from each other, to share knowledge of new concepts and to reflect on learning that resulted from colleague input. Ultimately, the interaction and exchange of information that occurred during the construction of the maps led to new questions, fostered the need for further explanations and facilitated multidisciplinary cooperation.

Richards et al (2013) used concept maps during a clinical case interactive discussion to promote vertical integration of basic and clinical sciences concepts. Medical students from 1st to 4th year developed concept maps during a clinical grand rounds presentation. The students perceived concept maps to be useful in understanding relationships between concepts of physiology and clinical medicine. Students reported that mapping was a worthwhile tool to foster critical thinking. However, students indicated that practice and time was required to develop concept maps.

Thus, concept mapping can promote the integration of basic and clinical sciences within curriculum development

and instructional design. To make this idea a reality there are a number of implementation strategies. First, through a collaborative effort, medical school curriculum leaders, teachers in different disciplines and medical students can create a series of concept maps to connect specific sections of the curriculum. Using an interactive cooperative process, these groups can then interact with each other revising the maps until they agree they have achieved their curricular goals. A similar process can link assessment and evaluation with curricular goals.

Second, basic science and clinician educators can create an integrated, baseline concept map about a topic (see Figure 4). Then they can provide students with the same key concepts from basic and clinical sciences asking students to construct an individual or a group map that includes those concepts. The teachers can then compare the student's map with the baseline concept map allowing opportunity for corrective feedback. In another example, faculty can create a concept map on a topic (for example bacterial pneumonia) that includes the clinical presentation, the diagnostic work up of the disease, the microbiology of the most common pathogens involved and the pharmacology needed to treat the disease. Such a map allows faculty to visualize their own integration process by checking for the presence of meaningful links. At the same time, another group of basic and clinical teachers can conduct a similar process and create a concept map on the anatomy, histology, the biochemical process and pathology of a patient with bacterial pneumonia. Such maps can serve as a guide to plan and deliver integrated units of instruction to the students. Teachers can then choose an instructional delivery method, which may range from interactive presentations performed by a group of teachers from different disciplines using pre-constructed concept maps, to students creating a concept map from scratch or the concept map may be used as study material within a flipped classroom approach.

Developing Clinical Reasoning. Clinical reasoning is a context dependent thinking and decision-making process that leads to clinical actions (Higgs, Jones, Loftus, & Christensen, 2008). Clinical reasoning includes a number of dimensions: knowledge, cognitive skills (such as analysis and synthesis of data), reflective thinking, contextual thinking (which includes the interaction between context and reasoning process) and mutual decision making (where patients play an active role in their own health care by participating in the decision making process) (Higgs et al., 2008). Additionally, according to dual processing theory, the clinical reasoning process relies on two systems. The first system (intuitive) is fast, involves pattern recognition and has low cognitive awareness along with a high emotional component. The second system, is slow, analytical and has a low emotional component along with a high cognitive awareness (Croskerry, 2009).

Problem and knowledge representation are key concepts to consider in the use of concept mapping to promote clinical reasoning. Problem representation may constitute a step between data acquisition and hypothesis generation because the representation helps the clinician to focus and understand the clinical problem and its solution. Information processing is also an important aspect of clinical reasoning. Information processing can be defined as an approach to analyze a cognitive task as "a set of steps in which an abstract entity called information is processed" (Anderson, 2005, p. 11). Knowledge representation, which is essential to information processing, entails the way knowledge is symbolized in the cognitive system.

Connections among concepts are the core elements giving an integrated structure its meaning. Yet, more importantly, connections create the flexibility within the network that allows new thinking or adjustments, giving rise to an elastic flexible integration structure that can more easily suit the reasoning required by ill-structured problems of clinical medicine. Thus, students' ability to make connections seem crucial for the ultimate development of an elaborated network.

Further developing the idea of knowledge representation, West et al. (2000) in a pretest/posttest study in medical education assessed the effectiveness of concept maps. In this study, concept mapping assessment (CMA) scores did

improve after course instruction but CMA scores did not correlate with final course or standardized test scores. According to West et al. (2000), "the absence of a positive correlation suggests that CMA measures a different knowledge characteristic than do multiple choice examinations" (p.1109). Therefore, concept mapping assessment has the potential to evaluate how medical students or residents organize and use knowledge in a way that traditional tests cannot. This type of assessment may also provide insight into why some students score well on objective written examinations but have difficulty with clinical application. There is evidence that although the quantity of knowledge is at an appropriate level for students, their level of knowledge organization may be poor, thus affecting their ability to solve problems and achieve a correct diagnosis (Bordage, 1994). Groves et al. (2003) demonstrated that students' clinical reasoning process might be somewhat underdeveloped, in particular, as related to their knowledge structures, which may not yet be developed in such a way as to allow accurate synthesis and correct diagnoses. Nonetheless, because comparing and contrasting similarities and discriminating features may enhance students' ability to foster organization of knowledge (Bowen, 2006), there is a need to understand how students organize their knowledge and make meaningful connections once they arrive at a clinical diagnosis.

How students view the structure of medical knowledge can affect their clinical reasoning and their diagnostic performance (Barrows and Feltovich, 1987; Elstein et al., 1978). Also how they organize, integrate and use knowledge structures can affect their ability to recognize meaningful patterns and generate effective explanations and strategies (Baxter et al., 1996; Bordage, 1994). Because concept mapping is a tool that allows opportunities to create meaningful connections among concepts within an integrated network of knowledge it seems to possess features that can promote understanding, practice, exploration and applications of clinical reasoning across learners and disciplines.

The applications of concept maps in clinical reasoning can take various forms. First, medical students can be asked, after a brief introduction to concept mapping, to draw a concept map from scratch on a topic of their choice. The topic may be an actual patient-centered clinical problem, a book chapter, medical journal article or a specific disease entity. The teacher can review the map and examine the types of concepts included and the accuracy of links established. This review is essential in assessing the cognitive processes of the student and providing feedback.

Second, the teacher can provide selected concepts to the learner and ask the learner to construct a map linking those concepts in a meaningful and accurate manner. Selected concepts should include those that are important to the curriculum or unit of instruction. The teacher will then be able to review the accuracy of the relationships between concepts and the meaning developed by the student. The interrelatedness of concepts will provide the teacher with a unique opportunity to evaluate the cognitive structures and critical thinking skills of the students. Also, the map creation will assist the teacher in identifying potential errors, knowledge deficits or misconceptions.

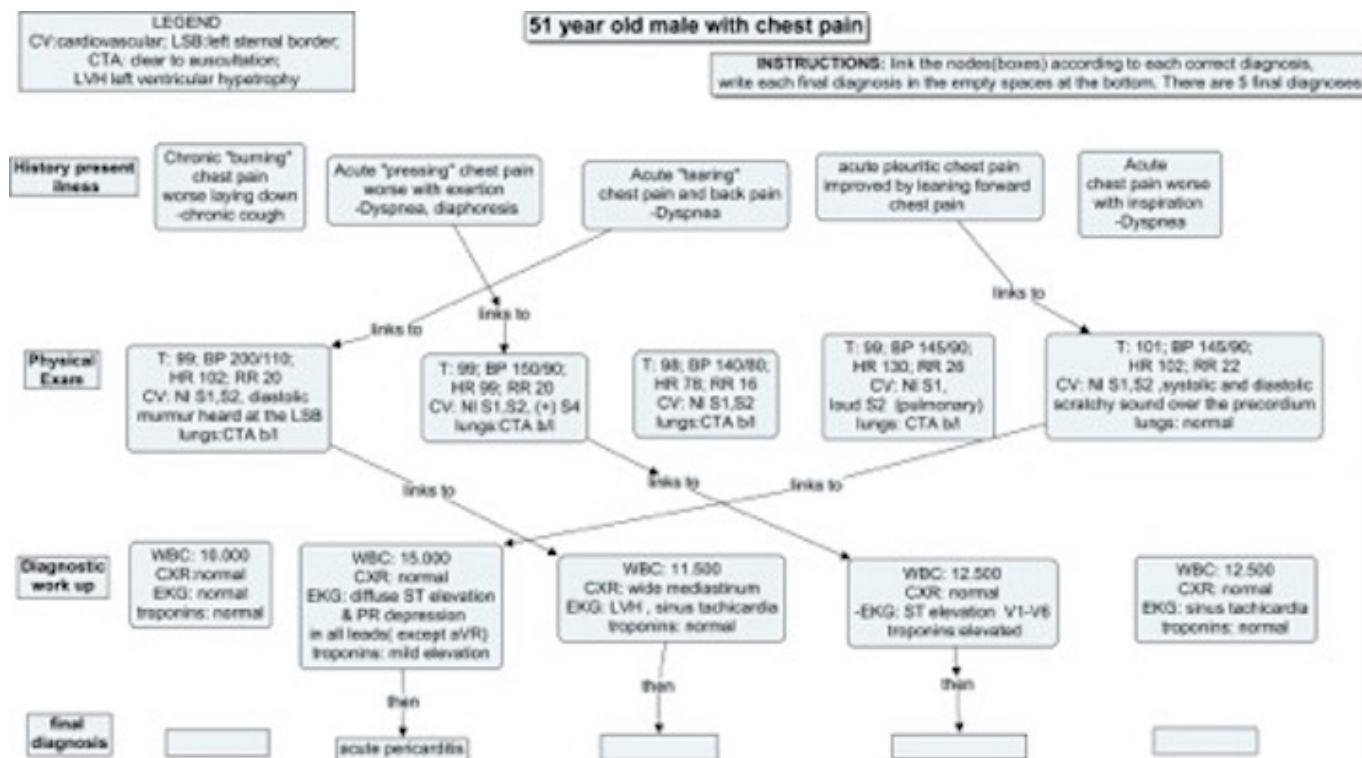Third, a clinical reasoning mapping exercise (CRME) may be used to promote clinical reasoning.

Figure 5: Clinical Reasoning Mapping Exercise (Torre, 2009)

As demonstrated in Figure 5, the CRME is an exercise in which the students are provided with a partially constructed) that shows categories (domains) and concepts (nodes) related to a clinical case. The top of the map lists the age, race/ethnicity and gender of the presenting patient. Then the history of present illness including four to five different clinical entities along with the type, duration and quality of the patient's medical complaint is presented. This information is included at the top of the exercise because it is consistent with the data gathering actions of a physician. Then listed vertically on the map, are the physical exam findings of each potential diagnosis and the possible diagnostic workup. The nodes contain more than one concept and are randomly placed in the map for the students to make the appropriate connections and arrive at four to five possible diagnoses. The final diagnoses however are not provided, thus the students are expected to arrive at a final diagnosis for each disease listed, ultimately becoming a differential diagnosis for that patient's complaint. Furthermore, if the exercise is aimed at learners with greater expertise, for example residents or faculty, nodes where the learner needs to enter a specific therapeutic plan for each diagnosis can be included.

There are a number of differences among tasks related to each of these clinical reasoning concept mapping exercises. Creating a concept map from scratch poses a higher cognitive load for the learner compared to one where concepts or links are provided to the learner. The former may be more appropriate when the main goal is to evaluate the knowledge structures of the learner and their ability to create connections. Conversely, the maps where direction is given may be more useful when the instructor wants to focus on assessing the student's level of understanding. Therefore, when teaching medical students early in their program, providing concepts from pathology and pharmacology coupled with a clinical scenario may be an effective learning tool. On the other hand, it may be more appropriate to ask senior medical students or residents to create a concept map from scratch, which ultimately requires a higher cognitive effort. Both applications are useful when assessing the student's ability to create and represent an integrated network of knowledge, ultimately allowing the instructor to evaluate the full depth of the reasoning processes.

The CRME however, is a more structured mapping exercise where the emphasis is on integration and creation of accurate connections. This learning tool promotes several strategies such as comparing and contrasting, discriminating among concepts or clusters of concepts, processing visual information, and ultimately, making a diagnosis. The CRME requires a shorter time commitment for the student and it is easier to score than a concept map. Using the CRME allows the instructor to give both individual and group feedback while identifying common misunderstandings. This allows educators to assess not only what a student is thinking but also where an error in thinking is taking place, what might have caused the error and in what context the error occurred. This provides educators with the unique opportunity to identify gaps in the students' thinking processes. At the same time, the instructor can then give immediate feedback by targeting specific areas of student weakness. It is during the creation of multiple connections and the development of a network of knowledge structures that a blend of analytical and non-analytical reasoning processes (Norman, 2005, 2009) may be utilized by learners.

Further research is needed to explore the use of dual processing theory and concept mapping in clinical reasoning. This research may facilitate an understanding of what cognitive processes contribute to diagnostic errors. Additional inquiries should be performed to examine the value of concept mapping in enhancing clinical reasoning skills, particularly with performance-based activities in actual or simulated clinical settings. Finally, correlational studies may be of interest to examine relationships between concept mapping and multiple choice question types of assessment.

Interprofessional Learning in Groups. Interprofessional learning is one of the more recent focus areas within medical education. Developing strategies for interprofessional learning can be based on the theoretical and practical aspects of learning in groups. According to Olenick, Allen, and Smego (2010), "interprofessional education is broadly defined as a teaching and learning process that fosters collaborative work between two or more health care professions" (p. 75). As such interprofessional learning and education focuses on team based work designed to facilitate patient care with the concepts of quality and safety in mind. According to the Interprofessional Education Collaborative Expert Panel (2011) there are four competencies for interprofessional collaborative practice, including, 1. Values/ethics for interprofessional practice, 2. Roles/responsibilities, 3. Interprofessional communication, and, 4. Teams and teamwork.

To meet the goals of interprofessional practice, medical and health professionals need to learn how to practice interprofessionally early in their careers. However, according to the Interprofessional Education Collaborative Expert Panel, "interprofessional education now suffers from a lack of guidance from appropriate theories" (2011, p. 33). Such theories could be used to guide the design, development and implementation of education programs that would focus on the four competencies of interprofessional practice. The theoretical premise of distributed cognition along with concept mapping as a learning strategy has implications in this developing area.

As demonstrated previously in this manuscript, the theoretical premise of distributed cognition relies on social, interpersonal and cultural factors. Additionally, cognitive events happen across individuals and the focus of distributed cognition is moving from individual experts to expert teams. Using concept maps as an instructional strategy is one way in which this can happen across multiple professions. For example, concept maps can be used to foster the development of the four competencies of interprofessional practice. In each of these competencies areas, actual clinical cases or problem based learning cases could be combined with concept mapping. Students in multiple professions could create a concept map of a case. In creating this concept map, students could identify where they see each of the four competencies of interprofessional education. Students could link the ethics/values, roles/responsibilities, communication and teams/teamwork to the clinical interventions of the case.

The first step would be to have students from each profession create their map individually based on their

understanding of the case from their own professional lens. Next, students would join an interprofessional group of multiple professionals. Each professional in the group would share their concept map and understanding of the case from their own individual professional perspective. After the individual sharing was completed, the group would be asked to develop a concept map that incorporates a new understanding of the case from multiple professional perspectives, again focusing on the four competencies of interprofessional practice. What this process provides is not only a socialization to individual professional roles but also a discussion and understanding of where and how those roles intersect in actual clinical practice.

Expanding on the use of concept maps in interprofessional learning, concept maps have also been used to foster collaborative group learning. There is evidence that development of collaborative group concept maps leads to greater learning and performance compared to creating individual maps (Kinchin, 2000; Kinchin & Hay, 2005).

Collaborative concept mapping also has applications in specific aspects of online learning (Simone, Schmid, & McEwen, 2001). The quality of the collaborative concept maps created in an online synchronous mode resulted in a better performance when compared to those developed in an asynchronous mode (Stoyanova & Kommers, 2002). The opportunity to add and modify concepts, create new connections and revise relationships in a synchronous mode makes concept mapping a very useful tool to analyze collaborative patterns, individual and group learning behaviors and the co-construction of knowledge. In another example, Hynes at al (2015) developed a curriculum for handoff training for medical students using an online group concept mapping process. Experts from four different European countries worked together to generate and sort ideas using concept maps in the group setting. Group concept mapping served to generate a series of learning outcomes that were ultimately used to design the handoff curriculum.

There are a variety of ways in which concept maps can be used in groups and interprofessional settings. These strategies can be used in face-to face instruction and online instruction. First, the teacher can ask a group of students (4-6) to create a concept map of a relevant clinical or basic science topic in a synchronous or asynchronous on line mode. The students can construct the map using the concept mapping software (Cmap Tools) in a virtual collaborative space. Figure 6 is an example of a concept map created by a group of students around a case of dyspnea.
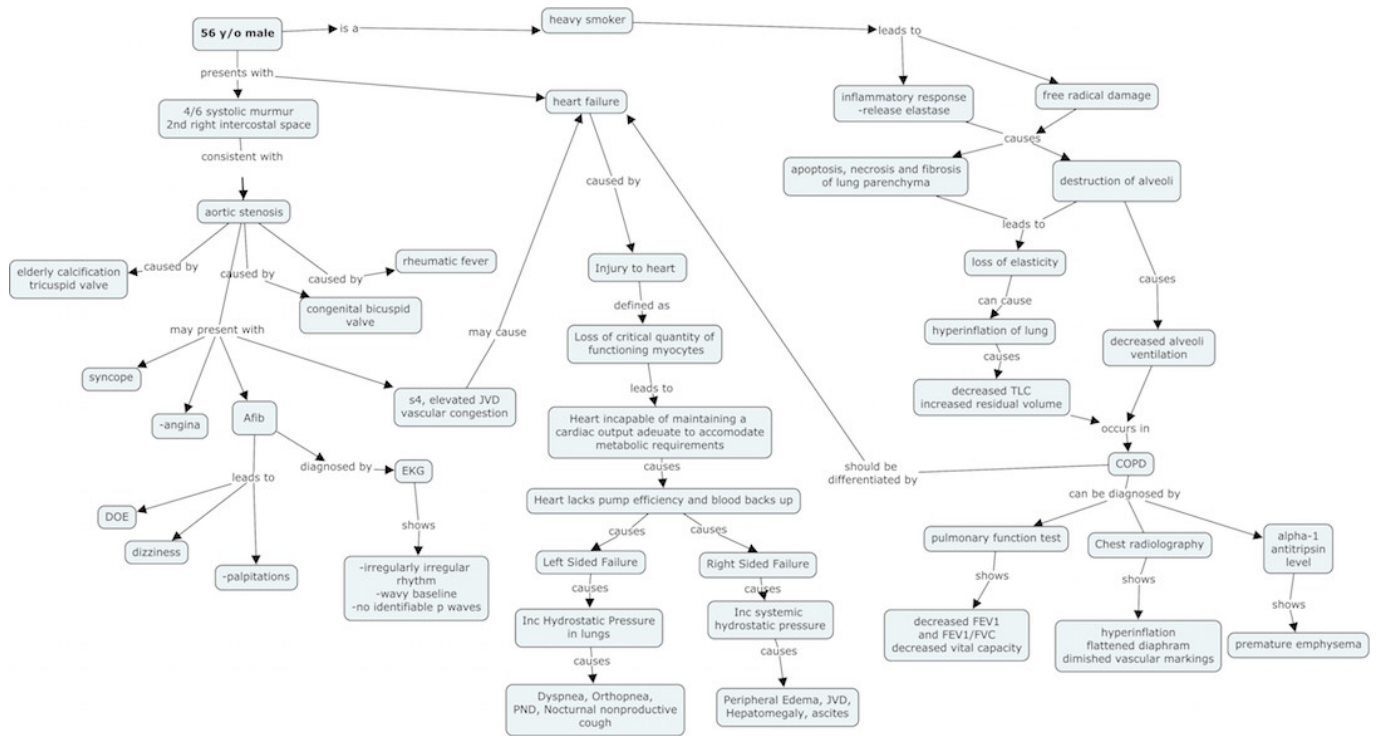
Figure 6: Group Concept Map

What is evident in this map, is that the group created a more complete and sophisticated map than most individuals can do alone.

Additionally, when maps are created in a synchronous online mode, the teacher can observe the creation of the map by the group in real time, visualizing the changes made along with the addition or deletion of concepts. This also allows the teacher to identify errors or misconceptions and evaluate the work of the group in real time. In an asynchronous online mode, the instructor can monitor the progress of the maps created by the group. The observation and evaluation of this process can allow the teacher to assess the group's knowledge creation, critical thinking skills and the students' interactions within group collaborative activities.

Second, the teacher can ask different groups of students to create a map and then ask each group to share their map with another group of students. The teacher can then evaluate possible changes and or revisions made by one group to the other group's map. Group map sharing allows the individual students and the group as a whole to view the work of other students, discover different approaches and obtain input while constantly learning from each other. Concurrently, the students can critique, challenge and provide input to their colleagues.

Finally, concept maps can be incorporated into most interprofessional education programs and activities being developed within medical, nursing, dentistry, pharmacy and social work education programs. The intent of creating an interprofessional map (similar to a group map) is to identify major concepts in a patient care case, the connections across bodies of knowledge and the linkages between different professions. The value of the concept map in interprofessional education is that it allows for active discussion, analysis and a reframed understanding of the roles, responsibilities, communication and teamwork needed in an interprofessional arena.

Conclusion

The use of concept maps in medical education is expanding and continuing to grow more diverse. In this article, the use of concept maps in three different areas was explored. Strategies were offered for the use of concept maps in linking basic and clinical sciences, facilitating the development of clinical reasoning and creating interprofessional learning opportunities in groups. Future investigation of the use of concept maps in medical education is still needed. Specifically, we suggest studies in the following areas:

- Methods by which concept mapping and curriculum mapping can be integrated,
- Outcomes of using concept maps and problem based learning concurrently,
- Understanding if/how concept maps facilitate the development of knowledge structures for clinical reasoning,
- Outcomes of using concepts maps to promote interprofessional education,
- Linkages between concept mapping and the development of expert performance, and,
- Effectiveness of using concept mapping in online environments.

Finally, based on the work shared in this manuscript concept maps can be a robust teaching and learning tool in medical education. As Novak and Cañas (2006a) state,

> While at first glance concept maps may appear to be just another graphic representation of information, understanding the foundations for this tool and its proper use will lead the user to see that this is truly a profound and powerful tool. It may at first look like a simple arrangement of words into a hierarchy, but when care is used in organizing the concepts represented by the words, and the propositions or ideas are formed with well-chosen linking words, one begins to see that a good concept map is at once simple, but also elegantly complex with profound meanings (pg. 31).

Take Home Messages

- Concept maps are a robust teaching and learning tool.
- Concept maps can be used in medical education to link basic and clinical sciences, facilitate the development of clinical reasoning and promote interprofessional education.
- Further research and investigation of concept maps in medical education is needed.

Notes On Contributors

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Appendices

Declaration of Interest

The author has declared that there are no conflicts of interest.