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Small-group problem-based learning as a complex adaptive system

Stewart Mennin[a,b,c,*]

[a]Department of Cell Biology and Physiology, School of Medicine, University of New Mexico, Albuquerque, NM 87131 0001, USA
[b]Office of Educational Development and Research, School of Medicine, University of New Mexico, Albuquerque, NM 87131 0001, USA
[c]Mennin Consulting & Associates Inc, Avenida Jacutinga 579 Apt 41, Sao Paulo, CEP 04515 030, Brazil

Abstract

Small-group problem-based learning (PBL) is widely embraced as a method of study in health professions schools and at many different levels of education. Complexity science provides a different lens with which to view and understand the application of this method. It presents new concepts and vocabulary that may be unfamiliar to practitioners of small-group PBL and other educational methods. This article looks at small-group PBL from the perspective of complex adaptive systems (CAS). It begins with a brief review of the current understanding and practice of PBL. Next some of the characteristics of CAS are reviewed using examples from small-group PBL to illustrate how these characteristics are expressed in that context. The principles and the educational theory in which small-group PBL are embedded are related to CAS. Implications for health professions education are discussed.

Keywords: Small groups; Problem-based learning; Complex adaptive systems; Educational theory

> To articulate and organise, and thereby recognise and understand, the problems of the world, we need a reform in thinking. And this reform is paradigmatic, not programmatic. It is the fundamental question for education because it concerns our ability to organise knowledge (Morin, 2001, p. 29).

1. Introduction: music and small-group problem-based learning (PBL)

Five jazz musicians walk into a nightclub to play. They each have defined roles in the band; piano, bass, drums, guitar, and saxophone. Each one has a unique history and experience in music. They have played together many times before. They chat informally about families, friends, recent events, and other gigs. There is excitement in the air because some special friends are in the audience and tonight is the debut of their newly recorded CD. They each know the list of tunes they will play. The lights dim. The sax player counts off the first tune, one, two, three, four…and so they begin. They open the show with a well-known jazz standard, Take the A Train.

*Corresponding author at: Mennin Consulting & Associates Inc, Avenida Jacutinga 579 Apt 41, Sao Paulo, CEP 04515 030, Brazil. Tel.: +55 11 5051 4967.
E-mail addresses: smennin@gmail.com, mennin@menninconsulting.com (S. Mennin).

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The music bursts upon the scene. Feet are tapping, bodies are in motion. Each of them is in the "pocket", a virtual space and a feeling created by the dynamic interaction between the percussion and the harmonic progression of the tune (piano, bass, and drums). Being in the "pocket" feels familiar, supportive and encouraging, a place in which they are free to play and improvise. The pocket continuously changes shape and feel from moment to moment yet remains supportive. They are listening intently at the same time they are playing; reacting to each other, the movement of the tune and their own feelings in the moment. There are subtle nuances in their playing as the tune emerges. Each time they play the main melody it's unpredictably different and yet readily recognizable. They are stylizing the melody as their own and it delights and stimulates them. The audience responds and the musicians feel the audience and respond as well. For the musicians, there are a few simple rules; play the tune without making mistakes, listen to each other constantly, stay together (musically and physically). Take the A Train emerges from the local interplay among five unique individuals and their surrounding context. The music did not exist until they began to play it and they cannot put it back from where it came. Six medical students and a professor walk into a room…

The students will be engaged in small-group PBL and, like the jazz musicians, will interact with each other according to a few simple rules in a safe environment from which learning and understanding will emerge. The dynamic formation of new patterns will be integral to their learning. The musicians and medical students are in that zone where multiple nonlinear local interactions lead to the emergence of new patterns of knowing and understanding. These new patterns influence them individually and influence the immediate environment; they are co-evolving. Changes in the immediate environment affect them as well. And so it goes in the complex world of small-group PBL.

This article looks at small-group PBL from the perspective of complex adaptive systems (CAS). It begins with a brief review of the current understanding and practice of PBL. Next some of the characteristics of CAS are reviewed using examples from small-group PBL to illustrate how these characteristics are expressed in that context. The principles and the educational theory in which small-group PBL are embedded are related to CAS. Implications for health professions education are discussed.

2. The essential nature of PBL

PBL, as originated by faculty at McMaster University in Canada (Neufeld, Woodward, & MacLeod, 1989), is based on the understanding that people know the world by interacting with it in the context of previous experiences. Today there are as many variations of PBL as there are practitioners (Barrows, 1986; Dolmans, De Grave, Wolfhagen, van der Vleuten, & Winjnen, 2005; Maudsley, 1999). What is important is that they are grounded and embedded in current educational theory and the application of principles of PBL (Bransford, Brown, & Cocking, 2000; Davies, Sumara, & Luce-Kapler, 2000; Norman & Schmidt, 1992; Regehr & Norman, 1996; Schmidt, 1993). The goal of PBL is for students, working in a small group (tutorial) with a faculty facilitator (tutor), to learn to explore, choose, question, disagree and explain the sciences basic to medicine necessary to understand the connections, dynamic patterns and processes involved in a particular health-related problem.

PBL is a method of learning in which students first encounter a problem followed by a systematic inquiry and reflection process (Barrows & Tamblyn, 1980). The problem comes first to stimulate and focus students' curiosity leading to an exploration and activation of pre-existing knowledge. Guided discovery with a tutor helps students to identify the edge of their knowledge, a zone between what they know and what they need to know. Discussion, self-directed learning, elaboration, timely feedback and reflection are processes characteristic of small-group PBL. Studies in cognitive psychology envision three roles for PBL: (1) the acquisition of factual knowledge in a context in which it will ultimately be used; (2) learning general principles and concepts in such as way as to facilitate transfer to new, similar problems; (3) the acquisition of prior examples that can be used for problem solutions on the basis of similarity or pattern recognition (Norman & Schmidt, 1992; Schmidt, 1993). PBL initially was promoted as an approach to developing overall problem-solving skills (Barrows & Tamblyn, 1980), however, subsequent research has shown that problem-solving skills and expertise are highly content and context dependent and do not generalize across subject domains (Norman & Schmidt, 1992).

2.1. The problem in small-group process

Learning and working in small groups feels natural. It is human. It is how we learn before we go to school and how we learn after we graduate. Students find PBL to be challenging, satisfying and motivating (Dolmans et al., 2005; Evensen & Hmelo, 2000; Schmidt, 1993; Schmidt & Moust, 2000). Small-group learning is the heart of PBL. It begins when students encounter a realistic health problem or situation that cannot be fully explained or understood by the members of the group at the level of their current knowledge. Problems are designed specifically to arouse and focus curiosity and to create a need to know upon which students will act collaboratively and individually. The problem stimulates students to activate what they already know, focus and facilitate sense making (Dolmans et al., 2005; Norman & Schmidt, 1992; Schmidt, 1993). Activation of prior knowledge is necessary but not sufficient for learning (Norman & Schmidt, 1992; Schmidt, 1993). Effective problems stimulate students to make connections with other problems they have studied and promote the application of new knowledge in a wide variety of situations.

2.2. Elaboration, discussion and exchange

Students activate and explore their pre-existing knowledge using a systematic process of discussion and exchange in the context of the problem (Norman & Schmidt, 1992; Schmidt, 1993). They identify areas that are not clear to them and that they need to understand better. These areas of uncertainty exist at the edge or frontier of their pre-existing knowledge (Abraham, 2003; Stacey, 1996; Vygotsky, 1978). It is at this edge/frontier that they will formulate questions (learning issues) which, when pursued through self-directed independent study and subsequently shared and elaborated through discussion in the group, will lead to new understanding.

The process is systematic proceeding from exploration and clarification of the initial problem to discussion of ideas in terms of the sciences basic to medicine, the formulation of learning issues, self-directed study, and at subsequent meetings, exchange, elaboration, and discussion of what has been learned as applied to the context of the problem. Clarification, integration and learning happen. New areas of uncertainty are identified as learning issues.

The exact nature of the learning issues and discussion cannot be predicted. In a general sense, 60–70% of the learning issues developed by the students will likely match the objectives the faculty intended when they wrote the case (Dolmans, Giselaers, Schmidt, & van der Meer, 1993). Different groups studying the same problem will create different yet similar learning issues. PBL also promotes the integration of the basic and clinical sciences in medical education curricula (Patel, Groen, & Norman, 1991) as cases tend to be thematically organized.

2.3. Feedback and reflection

Feedback is essential for learning and when timely has been shown to enhance transfer of learning in general and in PBL (Bransford et al., 2000; Needham & Begg, 1991; Norman & Schmidt, 1992). Time is set aside at the end of each session or at the end of the week for the students and tutor to reflect on how the group is working and what they might do to improve both substantively and procedurally. Individuals, including the tutor, reflect on their role in and contributions to the group, what they might do more of or less of the next time that could enhance learning, group process and satisfaction. Suggested reflections and changes may be reviewed at the start of the next meeting.

Reflection in and on action is essential to continued learning and development (Schon, 1983). It is the most difficult and least well-done part of small-group PBL. In a healthy learning climate, people listen to each other and value each other's insights. The tutor models this process for the students and helps them learn how to do it. When done well, it provides a continued source of renewal for the group and individuals while at the same time providing guided practice in the development of self assessment skills that are needed continuously during their medical education, professional practice and other activities.

2.4. Organization of groups

Students usually meet together with their tutor for 2–4 h twice a week. A case usually lasts 2–3 meetings after which time another problem is begun. Groups usually stay together for a period of weeks coordinated with curriculum units such as modules, phases, semesters, etc. The sequence of problems is predetermined by prior faculty planning.

2.5. Cases, tutors, and faculty development

Questions, observations and encouragement are used by the tutor to facilitate the group (Barrows, 1988; Barrows & Tamblyn, 1980). The tutor needs to be skilled and knowledgeable in the application of small-group process, the principles of PBL and those of education in general, and group reflection. Careful attention to the structure of case problems and more learning-centered guidance may be needed initially when students are new to PBL (Schmidt & Moust, 2000). Tutors in a learning-centered curriculum who are engaged in guided-discovery are not a primary source of content information for students (Barrows & Tamblyn, 1980). In the author's experience, a workshop on techniques and pedagogy of small-group PBL may be sufficient to enable faculty to begin their role as tutors, however, continued and advanced faculty development over time is necessary to sustain PBL programs and prevent teaching-centered learning from dominating tutor interventions.

3. Complexity science and small group PBL

A lot of learning and teaching takes place in small groups; research, clinical care, study, leadership, planning, etc. We are social organisms who live in groups where learning is a social phenomenon. Each PBL small group has its own history, background and priorities, its own way of making and studying learning issues. Each group, and each person in it, has a unique style and interest. Each small group exists in relation to its environment or landscape. Landscape is a term borrowed from evolutionary biology and refers to the local terrain and the many complex systems in it each seeking to optimize their success (fitness) in a system filled with conflicts, constraints and opportunities (Kauffman, 1995). Each group evolves by trying to optimize its learning, functionality and the degree to which it satisfies the needs of group members. The way each of these factors affects a particular group at any given time and over time can be understood in the context of complexity science. The language of complexity science can be as alien to educators and health professionals as educational jargon is to complexity scientists.

3.1. What is a complex problem?

"The word *complexus* means that which is woven together" (Morin, 2001, p. 31). The insightful work of Glouberman and Zimmerman (2002) illustrates this concept by comparing simple, complicated and complex problems. Following a recipe is a simple problem. The recipe is essential. Recipes are tested to assure easy replication. No particular expertise is required but cooking expertise increases success rates. Recipes produce standardized products. The best recipes give good results every time. An optimistic approach to the problem is possible.

Sending a rocket to the moon is a complicated problem. Formulae are necessary and critical. Sending one rocket increases assurance that the next will be OK. High levels of expertise in a variety of fields are necessary for success. Rockets are similar in critical ways. There is a high degree of certainty of outcome. An optimistic approach to the problem is possible.

Raising a child is complex. Formulae have a limited application. Raising one child provides experience but no assurance of success with the next. Expertise can contribute but is neither necessary nor sufficient to assure success. Every child is unique and must be understood as an individual. Uncertainty of outcome remains. An optimistic approach to the problem is possible (Glouberman & Zimmerman, 2002).

4. Characteristics of complexity science and CAS

A small group is complex. It is adaptive in that the participants individually and in groups are altered by and learn from their experiences. The group and people that are part of it are a system because they consist of a set of connected or interdependent people and things. Each person is a CAS with many interactions among diverse agents, internally and externally. The group is embedded in society and is affected by society. Complexity science involves the study of complex systems that exhibit nonlinear dynamics, self-organization and emergent properties (Capra, 1996). CAS are characterized by diverse agents interacting with each other capable of spontaneously changing by self-organizing (Zimmerman, Lindberg, & Plsek, 2001). Examples include small-group PBL, the stock market, a flock of birds flying in formation, metabolism, the nervous system, the immune system, the Boston marathon, a family health clinic, and people. CAS are nested in other CAS at different levels forming a multidimensional web of interactions (Capra, 1996).

4.1. Agents

Agents can be individuals in a group, groups of people in a community, or a society. Agents process information and large numbers of information processing events make up a CAS (Capra, 1996; Holland, 1998; Zimmerman, Lindberg, & Plsek, 2001). Agents are different from each other, have different histories and the capability of exchanging information with each other, themselves and their environment. Each agent has different information about their system and none have enough information to understand the system in its entirety (McDaniel & Driebe, 2001). It is the exchange of differences among agents under particular conditions that leads to self-organization. Individual students, the group, and groups are agents.

4.2. Self-organization

Self-organization refers to new emergent structures, patterns and properties that arise spontaneously and are characterized by multiple feedback loops and nonlinear dynamics in an environment (Capra, 1996; Maturana & Varela, 1987). It is the dynamic interaction between agents (group members) that leads to emergence. In small-group PBL, a realistic problem that stimulates a need to know among students functions as an information processing gradient between what is known and what is perceived to be needed to more fully comprehend the problem (a control parameter). Individuals and the group arrive at a new understanding collectively (self-organization) through discussion, exchange of ideas, dialogue, debate and sharing of information. There is no self in self-organization (Scott Kelso, 1995).

4.3. Linear and nonlinear

Linear is a line or a single dimension. Turning the volume up on your sound system increases the strength of the sound in direct proportion to the amount of movement of the knob. Nonlinear refers to the representation of a phenomenon as a curve in which small changes can result in large effects or large changes can result in small effects. A nonlinear system is characterized by components that are interactive, interdependent and exhibit feedback effects (Zimmerman, Lindberg, & Plsek, 2001). A single word or phrase during discussion of learning issues in a tutorial can result in a breakthrough, a clarification of a difficult explanation, an ''aha''. Some discussions go on and on and do not seem to lead anywhere.

4.4. Interconnections

Just having a lot of agents or students does not necessarily make a CAS. There has to be interaction. It is the relationships among agents that are most important for the emergence of patterns (Scott Kelso, 1995). In small-group PBL, the relationships between group members and the tutor is fundamental to self-organization and learning. On any given day, the dynamics of interaction and pattern formation are different. Some days the group is great and students leave feeling they have learned a lot, on other days the group seems dull and less productive. The difference is due in large part to the quality of interactions, which also affects the degree to which students study the learning issues and learn (Dolmans et al., 2005; Regehr & Norman, 1996).

4.5. Equilibrium and far from equilibrium

A system at rest is largely unaffected by internal or external changes since it returns to its original condition after being disturbed; a system that tends to remain at status quo. An example would be a tutorial group trying to learn without success or apparent change.

At a certain distance from equilibrium, a system behaves in nonlinear ways inherent in the system and new processes are set in motion (Prigogine, 1996). Appreciating far from equilibrium becomes an essential feature in describing nature. Living systems exist far from equilibrium, close to but not in chaos; at the edge of chaos (Stacey, 1996). Far from equilibrium is a place where the possibilities for self-organization and the emergence of new patterns are maximally possible (Kauffman, 1995). It is a place of creativity, of change, realization and insight (Csikszentmihalyi, 1996; Nachmanovitch, 1990). Important phenomena happen at the edge of chaos; cognition, metabolism, new organizational rules, self-organization. Learning takes place in a zone of complexity (Fraser & Greenhalgh, 2001) that has many similarities with Vygotsky's zone of proximal development (Vygotsky, 1978). Students are struggling to clarify a learning issue about acid–base balance in a newborn baby. They have all studied and feel they are close but still do not quite understand enough to put it all together. They decide to ask an expert to come meet with them.

4.6. Self-similarity

Two things or processes are self-similar if by enlargement or reduction one can be made to fit on top of the other. For example, all circles can be made to fit in a self-similar way (Davies et al., 2000). Nature is filled with patterns and processes that are self-similar. A fern leaf resembles the whole plant in a self-similar way. Other examples include cauliflower, clouds, the edges of coastlines, water ripples. Complex things and processes are not a function of size or scale since the level of detail is similar at different orders of magnitude (Barabasi, 2002). A small group has fuzzy boundaries that consist of rules of conduct, temporal limits and other boundaries that link the members together in an interdependent way with shared consequences. It exists within a society that has fuzzy boundaries, rules of conduct, culture, temporal limits and other boundaries that link the members together in an interdependent way with shared consequences.

4.7. Co-evolution

As agents in a CAS interact mutually, self-organize and new things emerge, the environment in which the CAS is embedded is changed by the presence of the newly emerged things; both are changed (Kauffman, 1995; McDaniel & Driebe, 2001). Students in a PBL group are discussing and sharing information about their learning issues relative to an outbreak of diarrhea in a village. A new understanding, a clarification may emerge for the group which affects the individuals in it in such a way as it influences subsequent discussions; co-evolution. Co-evolution deals with the impact of dynamic mutual exchanges that spiral through the system. For example, student learning in a PBL group is embedded in a larger system, the class, the medical school, the community, society, the health system and the emergent phenomena can ripple throughout multiple environments.

4.8. Control parameter

A control parameter is a variable outside the system to which the system is sensitive and that moves the system through different states (Abraham, 2003). It is a term from synergetics, the study of pattern formation phenomena (Scott Kelso, 1995). A teacher may choose a pedagogical method (control parameter) to perturb the resting state (attractor states) of students. If successful, self-organization (learning) occurs. If there is no immediate self-organization, the control parameter perturbation may disturb the system so that at some later point in time self-organization may occur (Abraham, 2003). A health problem that stimulates a need to know among a group of students functions as a control parameter. The group reacts to their perceived need to know by exploring their pre-existing knowledge, defining learning issues, reflecting, engaging in independent self-directed study and subsequent group discussion. This leads to individual and group self-organization (learning). Control parameters do not specify a particular outcome or contain a code for the emerging pattern. Rather it leads the system through the variety of possible patterns (Scott Kelso, 1995).

4.9. Phase space

Phase space is an abstract mathematical space in which all the states of the system can be plotted (Kauffman, 1995; Tennison, 2004). Every variable of a system is associated with a different co-ordinate in this space (Capra, 1996). A tutorial group can behave in many possible ways (its phase space). Over time, it will settle into a more well-defined and fairly regular pattern of working. At a particular moment, a plot of its variables would be a point in phase space. Over time, repeated plots would describe a particular trajectory in phase space for that group that describes the dynamic properties of the group's behavior. Different initial conditions in a tutorial will correspond to different starting points along the group's trajectory in phase space.

4.10. Attractor

An attractor is a metaphor for the trajectory of a CAS and refers mathematically to a fixed point in the center of the system which "attracts" the trajectory (Capra, 1996). There are different types of attractors and the dynamic properties of a system can be deduced from the shape of its attractor (Capra, 1996). In CAS, the variables are constantly changing. Time series analysis accounts for the fact that data points taken over time may have an internal structure (such as autocorrelation, trend or seasonal variation) that should be accounted for. These kinds of studies require repetitive measurements over fixed periods of time and introduce the idea of ageing data (Holt, 2004). Time is a factor in studies of deterministic systems since previous events influence those that come later. It is not yet possible to obtain data with the kind of temporal regularity necessary to reconstruct or describe the attractors of a tutorial group. It would be revealing if the structural equations model used by Schmidt and Moust (1995, 2000) to measure the strengths of the causal relations hypothesized between variables such as the amount of prior knowledge, quality of problems, tutor performance, group functioning, time spent on individual study, achievement, and interest in subject matter could be studied in more deterministic ways, looking at the variables over time, sensitivity to initial conditions, trajectories and attractors. Such an approach would be very different from the evaluation of average values at many places in the system, or averages over many systems (Holt, 2004).

5. Groups as CAS

The study of groups through the lens of complexity science is recent. Arrow, McGrath, and Berdahl (2000) have delineated five propositions that draw on systems theory, social network theory, dynamical systems theory and complexity theory as a means to understand groups. The propositions together with examples from small-group PBL will serve to recapitulate and extend the relationship between complexity science and small-group PBL.

5.1. Groups as open systems

"Groups, are open complex systems that interact with smaller systems (group members) embedded within them and the larger systems (organizations, classes, society) within which they are embedded. Groups have fuzzy boundaries that both distinguish them from and connect them to their members and their embedding contexts" (Arrow et al., 2000).

Students interact within the group with each other; outside the group with their classmates, faculty, families, etc. Individual members are themselves CAS. Group members negotiate exchanges inside and outside of the group that affect the group.

5.2. Causal dynamics in groups

"In the life of a group, three levels of causal dynamics continually shape the group. Local dynamics are activities between group members as they interact and carry out their tasks together. Local dynamics give rise to group global dynamics and are shaped and influenced by them. Global dynamics refer to the evolution of system-level variables that emerge from and shape local dynamics. Contextual dynamics refer to the impact of features in the group's embedding contexts that shape and constrain the local and global dynamics of the group" (Arrow et al., 2000).

Conversations between students and with the tutor are local dynamics in the context of working through a case problem, negotiating group roles, such as student coordinator and scribe, and reflecting at the end of a session. Global dynamics that could not exist without interactions among group members include development of shared learning issues, status among group members, and shared understanding of a problem. Local interactions forming coherent relations among the students and tutor are not aggregates of individuals or things. Contextual dynamics could refer to the module in the curriculum in which the tutorial is embedded, the class as a whole of which the group is a part, the community and clinical attachment or preceptorship experiences. These contexts may shape and constrain the local dynamics and therefore the global dynamics (Arrow et al., 2000). Another example could be the amount of time and number of meetings available for a tutorial are determined by curriculum planners and affect the type and depth of cases written, the rate at which case are opened, discussed and closed, the number of learning issues selected and the amount of study time allocated to them by students. Tutorials that take place during the clinical years or in community settings are shaped and constrained by local dynamics as well.

5.3. Group functions

Groups have two functions: one to complete student and curricular tasks and; two to fulfill group members' needs (social and emotional). The functional viability and integrity of the group as a complex system is tied to these two things. The integrity of the group (its completeness, its ability to remain sound and unimpaired) emerges as a third function from the group's pursuit of the first two functions (complete tasks and fulfill members' needs) and in turn affects the group's ability to complete group tasks and fulfill the needs of group members (Arrow et al., 2000).

This proposition points to the quality of the interactions among the students and between the students and the tutor and illustrates co-evolution of the group members and the group. Maintaining group integrity requires all group functions be interdependent (Arrow et al., 2000). The need to maintain the integrity of the tutorial is shared by everyone including the tutor. When students encounter PBL for the first time, they are less mindful of maintaining group integrity and more focused on learning tasks and personal and social needs. The tutor has a greater responsibility for group integrity during the early stages of the group's history. One strategy for developing high integrity early in the life of a tutorial is to establish mutual agreement about ground rules including frequent meaningful reflection and feedback. When the group is functioning with high integrity, the students are motivated to study more and deeper (Dolmans et al., 2005).

The priorities of the group vary as the group evolves. The balance between achieving tasks and social needs is self-regulated by the members of the group (Arrow et al., 2000). This is an example of local dynamics with multiple feedback loops. Students sense and process information, consciously and unconsciously, about the gap between the current condition of the group and needed future state. When students perceive the gap to be too wide (a control parameter) there is a spontaneous change (self-organization) in the group's focus and function (Arrow et al., 2000). Self-regulation is a feature of a CAS (Maturana & Varela, 1987). Group members, and especially the tutor, have to be tuned into this process and pay particular attention to: (a) what the preferred state and direction of the group is; (b) information that indicates the group and or some of the students are drifting off course; (c) methods and techniques for getting back on course (Arrow et al., 2000).

Groups are not machines and are capable of learning to change their own balance and find creative ways to sense and respond to information. Frequent individual and group reflection promotes this process because it is timely and local. Other specific strategies for dealing with problems (drifting off course, ineffective communication, etc.) in small-group PBL has been described (Dolmans, Wolfhagen, van der Vleuten, & Winjnen, 2001; Hitchcock & Anderson, 1997; Schwartz, Mennin, & Webb, 2001).

Multiple feedback loops create nonlinear effects. It takes time for a tutorial group to "come together," for teams to learn to work smoothly and effectively. As tutorial groups (CAS) learn, they tend to increase in complexity over time. The number of dynamic patterns tends to get longer and to increase in variety. The implications are that single observations or sampling of the tutorial provides limited evidence of what a group was earlier or will become in the future (Arrow et al., 2000). If there is a different tutor every case, it will be difficult to assess progress and provide temporally meaningful feedback. To paraphrase a popular setting, if you have seen one group, you have seen one group.

5.4. *Group composition and structure*

In groups, three types of elements (students who become members of the group, intentions that are embodied in the group tasks, and resources that become the group's technologies) are linked in a functional network of member-task-tool relations called the coordination network (Arrow et al., 2000).

The dynamic structure of the PBL group is made up of different combinations of these elements. The group may have students capable of completing their tasks and all the resources it needs and still fail to function effectively if the students and tutor do not develop a coordinated understanding (mindfulness; metacognition) of their collective work as learners, and the use of technology and resources together. The links between local, global and contextual dynamics form networks that vary depending on initial conditions, external and internal influences. Reductionistic approaches to studying CAS do not work. Breaking a CAS system down into its parts and varying them one at a time will not provide an accurate picture of a group that is strongly interconnected. When a new member of the group comes in, even when one person is absent for a meeting, all the links with members, tasks and resources are reconfigured (new attractor states).

5.5. *Modes of group life*

"The life of a group can be characterized by three ordered modes that are conceptually distinct but have fuzzy temporal boundaries: formation, operation, and metamorphosis (end and dissolution)'' (Arrow et al., 2000). As the group forms (emerges), students, intentions, and resources become organized into an initial network that delineates the group as a bounded (fuzzy) social entity. As the group works together to achieve its learning goals and fulfill member needs, the students and tutor elaborate, monitor and modify the coordination network established during group formation (groups learn and co-evolve).

When a group first forms there are a very large number of possible local interactions that could occur. Over time, the group's global dynamics 'settle' into a more limited set of behaviors in the larger space of all possibilities for that group (CAS). For example, students may repeatedly sit in the same place in the room, the group may develop patterns of using and discussing resources (some will read from notes and books more than others), group leaders emerge, patterns of beginning and ending a case problem become established, etc. The pattern of global dynamics is the group attractor, their behavior in phase space moving along a trajectory in time. The students and tutor learn from their experience and adapt to events occurring in their embedding contexts, i.e., visits to communities, clinical skills sessions, practicals, etc. There is continual mutual adjustment and adaptation (co-evolution, self-organization) among the group members, resources, technology and the group as a whole.

6. Discussion

It is common in the history of western science to reinterpret existing knowledge in the light of new technologies and concepts. William Harvey described the heart as a pump at a time when the mechanical pump was a new and contemporary technology. Cognitive psychologists adopted the metaphor of information processing, storage and retrieval from the language of computer scientists. The diffusion of complexity science concepts into education opens another dimensionality in the history of understanding how people learn about and know the world in which we live. It offers new perspectives on the nature of causality, knowing and learning that focus on the stability or instability of dynamic patterns and interactions; changes in a system over time and the conditions that promote self-organization and the emergence of learning (Abraham, 2003; Arrow et al., 2000; Davies et al., 2000; Fraser & Greenhalgh, 2001; Scott Kelso, 1995).

There have been many publications, discussions and debates about the effectiveness of PBL and its outcomes (Albanese & Mitchell, 1993; Dolmans et al., 2005; Vernon & Blake, 1993). ''It is evident that the interventions associated with PBL are multiple and each has a demonstrable effect, some positive–some negative… Far more likely is the possibility that there are complex interactions among many of the treatment components, so that any estimate of effectiveness must account for these interactions.'' (Norman & Schmidt, 2000). These authors acknowledge that the study and comparison of curriculum interventions like PBL will ''invariably confound attempts to seek cause–effect relationships, and simple experimental strategies like randomization will hardly remedy the situation'' (Norman & Schmidt, 2000).

An interdependent network of dynamic patterns and relationships does not lend itself to study using dependent and independent variables. Recognizing that a system is complex and has emergent properties requires a different perspective on causality. It may be more fruitful to study the contextual factors that constrain local interactions without determining the outcome. The whole pattern of global dynamics that emerges from local actions can shift when the context changes or can stay the same depending on the history of the system, the type of contextual changes and the initial conditions. It makes more sense not to try to predict average values for local level actions at a particular time or aggregated over time. Future curriculum designs and research studies that recognize small-group PBL as a complex adaptive system and focus more on the dynamics of learning as a self-organizing event emerging from interactions among multiple factors are more likely to shed light on how and why PBL is or is not effective.

PBL has revived the role of conversation as an important method of learning in the health sciences (Wheatley & Kellner-Rogers, 1996). The propositions put forward by Arrow et al. (2000) for small groups support and extend principles of learning for PBL (Norman & Schmidt, 1992; Schmidt, 1993) as part of the complexity paradigm shift. It is a perspective that illuminates group dynamics in a way that can help tutors and students understand interactions and learning through a new lens.

Many difficult problems in health care systems (Lewin & Regine, 2001; McDaniel & Driebe, 2001), family practice clinics (Miller, Reuben, McDaniel, Crabtree, & Stange, 2001), doctor–patient communication (Suchman, 2006), and medical education (Fraser & Greenhalgh, 2001) can be improved with leadership, management and education concepts based on complexity science. The challenges faced by leaders, faculty members and workers at health professions schools and academic health science centers lend themselves to approaches based on complexity science.

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