Scientific collaborations as complex adaptive systems

Abstract: This paper suggests that complexity theory can provide tools and insights into scientific collaborations. By using six propositions, which were established by observing the qualitative properties of chaotic systems, examples of how the most important features of complex adaptive systems exist in scientific collaborations are provided. (1) Scientific collaborations are potentially complex adaptive systems because of the many counteracting forces in them. (2) A basic protocol in the formation of a scientific collaboration could lead to a very complex system due to the tendency of forming non-linear relationships among the counteracting forces. (3) More need to be thought about the concept of equilibrium of scientific collaborations as their mortality requires a different approach than the current organizational theories. (4) Prediction impossibility is controversial. (5) The emergence of collaborations could be explained through 'self-organization'. (6) Actions' irreversibility exists.

Key words: scientific collaboration, complexity theory, chaos theory

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As the world faces ever more complex scientific challenges such as climate change (IPCC, 2007) and destructive pandemics (WHO, 2009), successful negotiation of these challenges relies on multi-institutional scientific collaborations, an emerging model that suggests new organizational forms and new patterns of work. Thinking of scientific collaborations as complex adaptive systems could be a new way of improving our understanding of what scientific collaborations are and how they can be optimized. While some scientific collaborations may be relatively small and short-lived compared to traditional business organizations they are no less complex. Complexity theory provides a novel look at scientific collaborations because of its ability to explain and make sense of unique, unrelated or one-time events is considered (Thietart & Forgues, 1995: 19). The current literature does not specifically focus on scientific collaborations but on innovations, partnerships, alliances, and collaborative networks that span science, technology and industry through examining relationships and transactions. Except for Shrum, Genuth & Chompalov's book '*Structures of Scientific Collaborations*'(2007) the research is limited to being a component within a larger project (Guston, 2000; Pielke, 2007) or case studies and bibliometric studies.

Knowing more about scientific collaborations can help collaborations perform more efficiently and can assure that funds are used most efficiently to tackle complex scientific problems. Significant research funding is allocated each year. For example, in the U.S. between 2000 and 2005 the ratio of research and development expenses in gross domestic product was (GDP) 2.68% which translates to approximately $333 billion per year (UNDP, 2008). This is larger than the GDP of 149 countries (World Bank, 2009). In the U.S. almost 1.38 million people are conducting research, most of which is done collaboratively (UNDP, 2008). Revealing the dynamics of scientific collaboration would benefit every stakeholder in the society: governments, policy makers, researchers, companies, and citizens. In addition, science and research indirectly affects the economy by creating new products and services (Guston, 2000: 66)

This paper will introduce an overview of the nature of scientific collaborations and will suggest how a new approach using complexity theory can provide tools and insights into these important organizations.

Scientific Collaborations

Since the beginning of 20th century, collaboration is the primary manner in which science is performed. The size of the collaboration could be as small as a co-authorship between two authors for a scientific publication and as big as LIGO (Laser Interferometer Gravitational-Wave Observatory) which includes 50 institutions over 11 countries coordinating research on detecting gravitational waves (LIGO, 2008).

This paper focuses on multi-institutional scientific collaborations. This type of scientific collaborations dates back nearly a hundred years when, in 1918, during the dark days of the Spanish Influenza pandemic, William H. Welch coordinated teams from universities, government, and the private sector to find a cure to the disease (Barry, 2004). ‘Big science’ projects, which are large-scale projects that need vast resources, funded by national governments or groups of national governments are another example. These include the ‘Manhattan Project,’ in effect from 1941 to 1946, which coordinated scientific work at more than 30 sites across the United States, Canada, and the United Kingdom to develop the atomic bomb (Rhodes, 1986); and the National Aeronautics and Space Administration (NASA) which was established to ease American’s concerns over Sputnik, the first Russian satellite (Gregory & Miller, 1998).

Complexity Theory

Organizational studies can be traced back to the end of 19th century (Barley & Kunda, 1992); however, complexity theory did not receive much attention until the 1990s. Complexity theory has become a comprehensive view of explaining the dynamics of organization. In order to have a better understanding of complexity, the difference between linear and non-linear models needs to be explained.

Linear modeling can be considered a antecedent of Descartes. Linear modeling has dominated the scientific world for almost 300 years because of its freshness, competence and convenience for calculations. Basically, linear systems are simple and deterministic, and therefore, manipulated or at least predictable. It means, if a phenomenon could be modeled linearly, it could be controlled. The main hypothesis behind this view is that a phenomenon is the aggregation of its components, so it should be broken down to its smallest units in order to understand it. However, many phenomena in life are neither linear nor can be reduced to its simplistic units (or both). In mathematics, the inability of linear analysis to explain non-linear systems is proved by Poincare; that is, a system is more than the sum of its parts (Waldrop, 1992).

In science, complexity tends to be ignored. The complexity of a phenomenon cannot be totally measured; hence, parts of the phenomenon are not recorded. This happens because “modeling the nonlinear outcomes of many interacting components has been so difficult that both social and natural scientists have tended to select more analytically tractable problems” (Anderson, 1999: 217). This produces deficient and incomplete reflections of reality. Thus, scholars end up having a discipline that is not connected to life and it does not help us to control or predict phenomenon as a result of its dependency to linear modeling.

In the 1960s, increased computational power resulted in increased interest in studying non-linear systems (Gleick, 1987). Physicists, meteorologists, economists and chemists adapted non-linear models to their disciplines. The main difference between linear and non-linear system is the center of attention given by researchers: interaction. Instead of focusing on units, in complexity theory, researchers focus on interactions.

Interaction is an intricate relationship among units and is generally short ranged (Cilliers, 1998: 4). For example, information is generally received from immediate neighbors. As the information travels unit through unit, it can be enhanced, suppressed or altered in many ways, such as the telephone game. Positive and negative feedback loops exist in interactions. Everything related to the system could be found in interactions and the level of analysis becomes interactions in complexity theory.

The result is called chaos theory; it later evolved to complexity theory. Nobel chemist Prigogine (1997) argued in his book '*The End of Certainty*' that this new paradigm is interested in instability, disorder, diversity, and non-linear relationships rather than the traditional mechanistic Newtonian view which dealt with stability, order, equilibrium and linear relationships.

Complexity Theory and Organizational Studies

Complexity theory focuses on "organizing rather than organization" (Weick, 1979) and prescribes that "…chaos is a science of process rather than state, of becoming rather than being" (Gleick, 1987: 5). It is continuous recreation of interactions and relations between units. It is this continuous recreation, redefinition and emergence that makes it harder to understand, predict and equalize. Thietart & Forgues (1995) took these features of non-linear systems and introduced six propositions in an effort to apply chaos theory[i] to organizational studies. In 1999, another six insights were added (Anderson, 1999) although some overlap with the earlier list. In the following explanations of these insights I also provide examples of how they exist in scientific collaborations.

1. Potential:

- "Organizations [collaborations] are potentially chaotic" (Thietart & Forgues, 1995: 25).
- "Complex patterns can arise from the interaction of agents that follow relatively simple rules" (Anderson, 1999: 218).

Simple rules could lead to complexity easily. For instance, chess has basic rules (6 different pieces which means 6 different moves and totally 32 pieces) but it is one of the most complex games ever created. In an organization every unit is a piece and each one of them has infinite options to move. According to Thietart and Forgues (1995) the countless counteracting forces in organizations increase the likelihood of chaos. As these counteracting forces pull organizations to different directions, the behavior of organizations becomes incomprehensible. Counteracting forces could lead to information gaps among the members through different interpretations by the members.

An unfortunate example of this is the Columbia space shuttle disaster. Vaughan (cited in Milliken, Land & Bridwell-Mitchell, 2005) draws attention to the different lenses of engineers and managers in NASA. Engineers realized a debris strike occurred at the launch; however, the managers did not think that it was important because strikes had not caused problems before. Trying to fix it would be costly, so they decided to continue the mission as planned. The science-oriented set of goals was inhibited by operational perspective, causing the disaster. On the other hand, counteracting forces are also a tool of developing new responses to changes in the environment, and thus, by increasing the adaptability of the organization, it increases its chance of survival, which is called ‘coevolution to the edge of chaos’ (Anderson, 1999; Pascale, Millemann & Gioja, 2000).

The reason behind this argument is the existence of many counteracting forces in a system. Like every organization, in scientific collaborations there are many counteracting forces because of their multi-disciplinary and multi-institutional structure. Each agent in the system is a force in the system. For example, Powel (1998) describes the disciplines in biotechnology research:

> “The initial research—most notably Herbert Boyer and Stanley Cohen's discovery of recombinant DNA methods and Georges Kohler and Cesar Milstein's cell infusion technology that creates monoclonal antibodies—drew primarily on *molecular biology* and *immunology*. The early discoveries were so path-breaking that they had a kind of natural excludability, that is, without interaction with those involved in the research, the knowledge was slow to transfer. But what was considered a radical innovation then has changed considerably as the science diffused rapidly. *Genetic engineering*, monoclonal antibodies, polymerase chain reaction amplification, and gene sequencing are now part of the standard toolkit of *microbiology* graduate students. To stay on top of the field, one has to be at the forefront of knowledge-seeking and technology development. Moreover, many new areas of science have become inextricably involved, ranging from *genetics, biochemistry, cell biology, general medicine, computer science, to even physics and optical sciences*.” (Powel, 1998: 232)

Each discipline and each level of researcher (graduate student to professor) has its own agenda. Moreover, different types of institutions (research universities, start-up and established firms, government agencies, nonprofit research institutes, and leading research hospitals) are also needed to do the research, find funding, conduct clinical trials, get approval and license, and market the product (Powel, 1998: 233). Each unit (individual, discipline and institution) is a force and they are intertwined. Powel's little piece about biotechnology demonstrates the potential of complexity in one field and it offers insight into every multi-institutional and multi-disciplinary scientific collaboration.

2. Non-linearity:

- "Complex systems resist simple reductionist analyses, because interconnections and feedback loops preclude holding some subsystems constant in order to study others in isolation" (Anderson, 1999: 217).

This is the key feature of a complex system. When a part of a system is examined by itself, it means it is isolated from the other parts in the system. Hence, the analysis will be wrong because the interactions between the parts are going to be missed. Moreover, feedback loops could weaken or strengthen certain behaviors and processes are going to be missed. These loops are important because they directly affect the equilibrium of the organization.

The Spanish Flu, as detailed in Barry's book (2004), provides an excellent example of scientific collaboration and non-linear relationships. The Spanish Flu killed 100 million people and sickened many more. Thousands of researchers worked to find a cure. Their work patterns differed; some individuals shared information and joined forces to work together while others stayed within their silo believing that the flu was a result of biological warfare efforts. Welch, an agent of the scientific collaboration interacted with a large number of elements: hospitals, Red-Cross, media, private sector, government and military (Barry, 2004).

NOTE: Insert Table 1 approximately at this point.

An analysis of this situation suggests interactions were non-linear. Some of the researchers hated each other, some were performing under Welch's charisma; some wanted to become famous by finding a cure and some just wanted to help humanity. Positive and negative feedback loops existed. For instance, Welch, Dean of Johns Hopkins Medicine Department and leading figure of American Medicine, alerted the military to get prepared for the pandemic (positive feedback). However, the governor of Philadelphia did not listen to the doctors and did not declare martial law; as a result, flu hit Philadelphia very hard (negative feedback). Agents of scientific collaborations interacted with others that were physically proximate: colleagues who work in the same hospital, research center or university. With the telegraph and newspapers, they also accessed to information that did not originate in their region.

The system was certainly open. Because of the World War I, troops were deployed to many countries and carried the disease with them; the quarantining the disease was not possible. The virus that caused the Spanish Flu, mutated in different parts of the world. Without isolation of the disease and with mutations of the virus, equilibrium did not exist for many years. Other researchers in the world also worked on the virus to find a cure. However, due to the war, prevailing opinion was that the flu was biologic warfare which prevented joint efforts to find a cure, especially in Europe. Agents of scientific collaborations acted on the available information. They followed the wrong cues and had incorrect diagnoses which increased the death toll.

The example above shows the non-linear complex relationships between many units in the system. An isolated analysis of one unit does not provide the "what, why and how it happened" in reality. The whole systems behavior cannot be found in one member's behavior as it is supposed to exist in linear systems. In every scientific collaboration non-linear relations exist and they dominate the system.

3. Equilibrium:

- “Organizations move from one dynamic state to the other through a discrete bifurcation process” (Thietart & Forgues, 1995: 25).
- “Many dynamical systems do not reach either a fixed-point or a cyclical equilibrium” (Anderson, 1999: 217).

Equilibrium might not exist and if it exists, it is not stable. Changes to the system happen abruptly, causing the system to move from one state to another suddenly. Whenever the order of counteracting forces change, organization moves away from or towards equilibrium.

In regards to scientific collaborations, the equilibrium concept should not have the same approach as that the business oriented organizations because in most of the cases, scientific collaborations have a life span –the funding period. Business organizations generally tend to avoid their death; therefore, when equilibrium is considered, organizational theories revolve around evolution, survival, flexibility, adaptation, and existence. Management literature can be characterized as focusing on the existence of companies. Scientific collaborations, on the other hand, are mortal by definition; they collaborate until a certain goal is reached. The members know it from the beginning and they do not try to escape from it or delay it. Therefore, the conscious or unconscious urge for evolution does not exist in their mental frameworks. Their goal is to die because by only achieving that goal they can fulfill their purpose of being, which is completing their project.

Theoretical exercises on equilibrium might direct scholars to new studies but this paperwill make a narrow equilibrium definition so that the disturbances (threats to equilibrium) that might prevent achieving the goal of the collaboration can be better understood. Equilibrium is being “on-track” regarding scientific collaborations work. If everything goes as planned in the project, equilibrium exists. Equilibrium exists as long as the systems works as it is supposed to be. As the work of scientific collaborations is planned, we can argue that, the system works in equilibrium. If something goes wrong, the goal could not be achieved; therefore, disequilibrium has to be dealt with.

Equilibrium might be disturbed by either an internal or an external influence. A conflict is an example of internal disturbance that might threaten the equilibrium. Shrum et al. (2007) define three types of conflict that threatens the equilibrium: conflict between project teams, with project management, and between engineers and scientists (p.164-76). In some of the cases they provide, the conflict was so big that the collaborations were terminated. An example of how disequilibrium threatens the survival of collaboration. As for external disturbance, NASA’s establishment is a good example. Before Soviet Sputnik’s launch, the air and space studies were coordinated by the Defense Advanced Research Projects Agency (DARPA) an agency that is responsible for the development of new military technology and is indirectly related to air and space studies. However, the Sputnik crisis filled the U.S. public with fear (Gregory & Miller, 1998: 13). A separate institution to work fulltime on air and space studies was needed. NASA was established and it adopted DARPA’s portfolio on air and space studies. An external disturbance led a restructuring in the U.S. air and space studies. To recap, like in complex adaptive systems, equilibrium might or might not exist in scientific collaborations; adaptation becomes a more important concept.

4. Prediction impossibility:

- “The behavior of complex processes can be quite sensitive to small differences in initial conditions so that two entities with very similar initial states can follow radically divergent paths over time” (Anderson, 1999: 218).
- “Forecasting is impossible, especially at a global scale and in the long term” (Thietart & Forgues, 1995: 26).

Because of many counteracting forces in the system, a small change (such as a small difference in initial conditions) could lead to a big difference. For instance, meteorologist Lorenz was too lazy to type .506127 into the computer while he was working on a climate model trying to predict weather, so he typed .506 (Gleick, 1987). The results were so different and unexpected that he started to work on this strange event and became one of the founding fathers of chaos theory.

Prediction impossibility could be controversial. Sometimes, prediction is possible in scientific collaborations (in regard to natural sciences). A group of researchers comes together to prove a hypothesis, which Thomas Kuhn (1962) referred to as “normal science as puzzle solving” (p.35).Kuhn argues that the duty of science is to do research according to the dominant paradigm in the field. The questions that are going to be asked are definite and the answers to these questions are almost definite as well. The duty of the researcher is to confirm the results in the current paradigm. Therefore, unless a descriptive study is planned, the results are predicted.

Sometimes, however, it is impossible to predict the results after a certain point. The space probe Voyager is a good example. In 1970 Jet Propulsion Laboratory (JPL) realized that due to the alignment of planets in the solar system, a space probe could reach to outer planets (Shrum, et al., 2007: 46). They alerted NASA and NASA organized a competition for the feasibility of the project. A collaboration was formed to conduct the project. In 1977, Voyager 1 and 2 launched to investigate Jupiter, Saturn, Uranus, Neptune and Pluto. Mission went smoothly and accomplished in around 15 years. However, Voyager 2 has kept sending valuable data after it passed Pluto; it is still sending. Recently, it has passed to the area which is called termination shock, the border of solar system, and will reach interstellar medium in 7 to 10 years (New Scientist, 2008). It will be the first man made probe that went outside the solar system and provide data about the deep space from first hand. This result is unpredicted. Nobody predicted that the probe will continue to work that long.

Another result in scientific collaborations is failure, and failure is not predicted. However, there is not enough data about failed projects as scientist report only their successes. One very famous exception for that is the Michelson-Morley experiment to prove the existence of aether, a medium for the propagation of light (Schaffner, 1972). Experiments led by Michelson and Morley, both American physicists, had conducted a series of experiments and failed to prove aether. However, proving that aether does not exist was also an important result. Michelson won a Nobel award for his efforts. These examples demonstrate that prediction is not always impossible as complexity theory envisages; however, there is no doubt that uncertainty exists. In some cases, everything works according to the plan, in some cases they do not but with some adjustments certain goals could be achieved. In some cases, on the other hand, there is only failure. More research in this area is needed. If criteria for prediction could be established, resources could be allocated more efficiently accordingly.

5. Strange attractors, self-organization and fractals:

- “When in a chaotic state, organizations are ‘attracted’ to an identifiable configuration. … When in a chaotic state, organizations, generally, have a fractal form” (Thietart & Forgues, 1995: 26-7).

- “Processes that appear to be random may be chaotic, revolving around identifiable types of attractors in a deterministic way that seldom, if ever, return to the same state. … Complex systems tend to exhibit ‘self-organizing’ behavior” (Anderson, 1999: 217-8).

Attractors are patterns eventually seen in chaos. The emergence of these patterns is related to the richness of the interaction between independent units; otherwise, they do not emerge (Weick, 1979). Organizations are open systems; they continuously import energy from their environments. This excess energy brings order to the chaos inside the organization. Units form behaviors, structures or processes. These new behaviors, structures and processes are called ‘strange attractors’. For instance, Isabella (1996) describes some stages for the interpretation of key events in an organization. At the anticipation stage, informal communication channels are formed ‘out of blue’ to convey rumors about the key event. The behavior, structure or process observed in small scale could be applied to explain the behavior in system scale (fractal form). During an economic turmoil, organizations with many smart and capable managers exhibit irrational behaviors like individuals because the managers who make decisions are the panicked individuals.

The concept of self-organization is important especially at the emergence of scientific collaborations. Self organization is “a property of complex systems which enables them to develop or change internal structure spontaneously and adaptively in order to cope with, or manipulate, their environment” (Cilliers, 1998: 90). Scientific collaborations most of the time are self-organizing entities. Some scientists (or sometimes only one) identify a problem that needs to be dealt with. However, the problem is too big to deal with alone. Additional resources (researchers, equipment, facilities, etc.) are needed. Basically, the need is the motivation to collaborate.

For instance, the Manhattan Project is a good example of self organization. Because of the Nazi regime, scientists fled from Europe and came to the U.S. (Rhodes, 1986). They were following the scientific advancements in Germany and given the success of combining science and technology with weapons production, they started to fear the Nazis might develop an atomic bomb when in December 1938 German chemists discovered nuclear fission. A concerned Hungarian Jewish citizen named Szilard tried to convince physicists in the U.S. to do research on the feasibility of atomic bombs but he did not gain official support. He asked Einstein to write a letter to Belgian Queen Mother not to let Nazis to access the uranium in Belgian Congo. Alexander Sachs, unofficial adviser of President Roosevelt, heard the matter and asked Einstein to write a letter to the President. Einstein wrote the letter to the President about the importance of having an atomic bomb. Th president appointed a Uranium Committee. After two years, the official government project had started and was named the ‘Manhattan Project’.

If we refer back to Cilliers’ (1998) definition above, Szilard felt the urge to cope with the environment. The environment had changed because German chemists found a way to make nuclear fission. He developed an internal structure that suggested that preventing Nazis to access uranium through Belgian Queen was the best idea. When Sachs became involved, he and Einstein changed the structure and contacted the U.S. President. The emergence of Manhattan Project follows the definition of self-organization.

Self-organization is not limited to the Manhattan Project only. Most of the scientific collaborations could be viewed as self-emergent. Shrum et al. (2007) examine the formation of collaborations. All of them are self-emergent even though they have different motivations to come together. Sometimes a scientist sees a research opportunity; sometimes a group of people sees that opportunity. In some, collaboration is the only way to recapitalize the funds because only with collaboration funds could be accessed such as the BIMA example mentioned above. None of the collaborators had enough funds to build a new telescope. Sometimes, it is the only way to do research. For instance, it is enormously expensive to build and hard to use a particle accelerator, so research in particle physics is always collaborative. The establishment of the European Organization for Nuclear Research (CERN) cost $8 billion and 5000 researchers took part in the last experiment (New York Times, 2008).

As for fractal patterns, there is not enough data. The aim of this paper is to demonstrate the need for the study of collaborations from complexity theory perspective. New studies could fill this gap.

6. Actions' irreversibility:

- "Similar actions taken by organizations in a chaotic state will never lead to the same result" (Thietart & Forgues, 1995: 27).

Above we noted a small change could lead to big differences in results. Since there will always be small differences in the events encountered by the organizations, the same prescription will not cure all the time. Tailor made solutions or at least adjustments to previous solutions are needed.

The irreversibility of actions suggests that similar actions do not lead the same results in chaotic states. There is not much data in this topic. However, I will provide an analogy to make my argument that it exists in scientific collaborations.

Earlier we note that scientific collaborations are mostly limited to either bibliometric studies or case studieswhich is a result of the unique structure of scientific collaborations and which prevents researchers from having generalizable findings. Shrum et al. (2007) argues that:

> “They (case studies) share a microsociological focus, a qualitative methodology, a cultural-anthropological or narrative orientation, and (owing to the research intensity required by the approach) an emphasis on single organizations, centers, or projects. …when the findings of case studies are contrasted, they display such diversity as to defy generalization” (Shrum et al., 2007: 8).

Three examples from their findings of previous case studies (Shrum et al., 2007: 9) demonstrate how hard it is to generalize case study findings. In the first one, Rubbia, a physicist, succeeds in lobbying to develop an accelerator and makes an important discovery; on the other hand, Spitzer, an astronomer, cannot secure any role in the construction of a telescope although he was the main scientist to lobby in NASA. The second example discusses the difference in power-sharing arrangement in particle physicists and geophysicists. The last is about the opposite views in particle physics about personal findings vs. common findings. The interesting thing about the last example is that both of them are from the same discipline. The nature of generalization is indeed similar to actions’ irreversibility. Generalization is a proposition asserting ‘something’ to be true either of all members of a certain class or of an indefinite part of that class. Thus, if it is not been generalized, then it means there are not any ‘something’ similar. On the other hand, actions’ irreversibility argues that similar actions do not lead to same results. According to actions’ irreversibility, the probability of experiencing the same conditions is so low that it should be neglected because even a small difference in the conditions will result in a huge difference in the outcome. Hence, there is no need to generalize because there will be always small differences in conditions. By not being able to establish a literature on common dynamics of scientific collaborations, the current studies indicate that actions' irreversibility exists in scientific collaborations; hence, complexity theory could provide a new way to generalize findings.

Conclusion

In this paper, the need for research in scientific collaborations is addressed. Scientific collaborations are an important element of modern life. Scientific inquiry has been performed collaboratively since the 1940s and has direct and indirect influences in our lives. More has to be learned about scientific collaborations in order to increase their efficiency. Complexity theory could provide the knowledge to learn more.

Scientific collaborations are potentially complex adaptive systems because of the counteracting forces in them. A basic protocol in the formation of a scientific collaboration could lead to a very complex system. Their emergence is usually explained by one of the most important feature of complex systems: self-organization. Owing to the non-linear relationships among their units and their environment, linear modeling does not explain their behaviors. As every scientific collaboration is unique due to its members, objectives and the context that they operate, actions' irreversibility exists. However, more need to be thought about the concept of equilibrium of scientific collaborations as their mortality requires a different approach than the current organizational theories. Prediction impossibility is also a controversial feature.

In conclusion, in the complexity of contemporary scientific inquiry, current studies do not have all the answers. A new paradigm has to be employed to overcome the limitations of current research in the study of scientific collaborations and complexity theory can be a tool for the new paradigm.

Tables and Figures

Title	**Propositions**	**Examples**
Potential	Counteracting forces increases the likelihood of chaos in a system.	Columbia space shuttle disaster, biotechnology research
Non-linearity	Interconnections and feedback loops creates non-linear relations among units.	Spanish Flu
Equilibrium	Only dynamic equilibrium exists, if ever.	Establishment of NASA
Prediction impossibility	Forecasting is impossible, especially long term.	Space probe Voyager, Michelson and Morley experiment
Strange attractors & self-organization	Self-organized patterns arise in complexity.	Manhattan Project
Action irreversibility	For a complex adaptive system, encountering the same situation is improbable.	Examples from particle physics, astronomy, and geophysics

Table 1 – Six propositions and related examples from scientific collaborations

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[ii] Chaos and complexity are often used reciprocally.