Investigating Science Teachers' Understanding and Teaching of Complex Systems

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Investigating Science Teachers' Understanding and Teaching of Complex Systems

Abstract
This study investigates science teachers' understanding and teaching of complex systems. The field of complex systems is the study of how parts of a system give rise to its collective behaviors. Since the 1990s, scientific and educational agencies have advocated the importance of complex systems in science education. Despite this call for instructional emphasis in complex systems, recent studies have shown that students continue to have poor understanding of these systems.

Current efforts in addressing this problem have focused on promoting student learning of complex systems. There are also a few studies that examine this problem from a teacher perspective. While these endeavors have yielded various successes and discoveries, the findings concerning teachers' complexity understanding and instructional practices are not conclusive. This is because most studies are small-scale, involve selective teachers, or investigate singular aspects of complex systems understanding. In short, we have yet to gain a thorough insight of the extent science teachers understand and teach complex systems.

This research addresses the gaps directly by looking at science teachers' understanding and teaching of complex systems. It examines what they know and teach about complex systems, how their instructional practices may be influenced by their understanding and why the ideas may be difficult to comprehend and teach. This research was conducted with 90 11th and 12th grades science teachers across six Singapore schools. A mixed methods design was used.

The findings revealed that while science teachers might appreciate the complex nature of systems, their understanding was not comprehensive: few teachers had prior knowledge of this domain; and certain complex systems ideas appeared better understood than others. It was also found that complex systems ideas were conveyed in science lessons but the extent the ideas were taught was uneven. These ideas were conveyed more often in biology than in chemistry and physics, and certain ideas were more explicitly taught. Teachers with better complex systems understanding were also better able to convey these ideas in their lessons. Several reasons impeding teachers' understanding and teaching of complex systems were also revealed. Implications for research and professional development for science teachers are discussed.

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INVESTIGATING SCIENCE TEACHERS’ UNDERSTANDING AND TEACHING OF COMPLEX SYSTEMS

Sao-Ee Goh

A DISSERTATION

in

Education

Presented to the Faculties of the University of Pennsylvania

in

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ABSTRACT

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Sao-Ee Goh
Susan A. Yoon

This study investigates science teachers’ understanding and teaching of complex systems. The field of complex systems is the study of how parts of a system give rise to its collective behaviors. Since the 1990s, scientific and educational agencies have advocated the importance of complex systems in science education. Despite this call for instructional emphasis in complex systems, recent studies have shown that students continue to have poor understanding of these systems.

Current efforts in addressing this problem have focused on promoting student learning of complex systems. There are also a few studies that examine this problem from a teacher perspective. While these endeavors have yielded various successes and discoveries, the findings concerning teachers’ complexity understanding and instructional practices are not conclusive. This is because most studies are small-scale, involve selective teachers, or investigate singular aspects of complex systems understanding. In short, we have yet to gain a thorough insight of the extent science teachers understand and teach complex systems.

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1 INTRODUCTION

1.1 Chapter Overview

This chapter presents an introductory argument for investigating science teachers’ understanding of complex systems. Research goals for this study are also outlined.

1.2 Need of the 21st century

The 21st century world has become increasingly complex. For example, the way we communicate with one another has been unequivocally altered by communication technologies that connect individuals in multiple networks (Boyd & Ellison, 2007). The manner in which we resolve socio-environmental issues such as the Deepwater Horizon disaster requires the adoption of a systems-wide perspective where our problem-solving efforts have to consider not only the environmental and economic implications, but also the engineering capabilities we possess (NRC, 2011; NSF, 2011). In education, the approach to reforming school systems requires appreciating the complex ecologies that exist among and between students, schools, and larger communities (AERA, 2010; Fullan, 2003). Indeed, many research organizations and policy-makers have voiced that it is important to understand and learn about the complexities inherent in the systems and issues of the world (e.g., CSS, 2013; ISTE, 2007; NECSI, 2001; The National Academies, 2009; Partnership for 21st Century Skills, 2007). Even in science education, recent major science education reform documents such as the Next Generation Science Standards and the Framework for K-12 Science Education have explicitly conveyed that
the teaching and learning of science must include crosscutting systems concepts to make sense of the complexity in the scientific phenomena (NGSS, 2013; NRC, 2011).

This research relates directly to the teaching and learning of complex systems in science. What are complex systems? Briefly, a complex system can be defined as an organization of interconnected and interacting components that as a whole, exhibits systemic patterns and properties not obvious from those of the individual components (Mitchell, 2009; Yoon, 2011). The ways in which groups of cells function together to sustain life, herds of ungulates roam the savannah to look for food, and molecules and atoms collide randomly to produce macro-substances, provide some of the most vivid examples of how individual actions and interactions lead to large scale patterns (Goh, Yoon et al., 2012; Klopfer et al., 2009; Yoon, 2008). To understand the complexity in these systems is to be able to reason that the components interact with one another and with their environment in multiple, nonlinear ways, and recognize that the systemic patterns observed emerge from these component-level relationships (Booth-Sweeney & Sterman, 2007; Goldstone & Wilensky, 2008; Resnick, 1994).

In science, understanding complexity is important on two levels. First, it is central to science learning because many scientific systems such as weather systems, ecosystems, and body organs, are complex in nature (Bar-Yam, 1997; Bertolaso, Giuliani & de Gara, 2010; CSS, 2013; Kauffman, 1995; Yoon, Klopfer et al., 2013). Traditionally, science has often adopted a linear and reductionist approach, focusing on ‘breaking down’ these systems to their components for analysis of their behaviors (Mitchell, 2009). This approach simplifies the learning but does not do justice to the multiple interactions
among the components and inter-relationships with other systems which give rise to the systemic properties and patterns (Capra, 1996). Scientists have argued that we need to investigate not only the behaviors of the components, but also the relationships among the components, the system, and its environment so as to fully comprehend complex systems (Gell-mann, 1995; Wilensky & Reisman, 2006).

Second, while complex systems are important to understand in their own right, complexity researchers also believe that these systems have certain common properties that can offer a unifying perspective for interpreting diverse scientific phenomena (Crutchfield, 2012; Garnsey & McGlade, 2006; Goldstone & Sakamoto, 2003). For instance, the complex systems ideas of emergence and self-organization are seen as equally salient in understanding evolution, gas systems, electrical circuits, and even socio-scientific issues such as genetic engineering (Kauffman, 1995; Gell-Mann, 1995; Pallant & Tinker, 2004; Perkins & Grotzer, 2005; Yoon, 2008; 2011). In the Next Generation Science Standards, the crosscutting concept of systems and system models describes the usefulness of considering flows of matter and energy into and out of diverse systems under investigation (NGSS, 2013). Researchers argue that this complex systems perspective provides us with new insights into science (d’Apollonia, Charles & Boyd, 2004; Goldstone, 2006); in fact, this perspective has been identified as the science of the 21st century, offering “path-breaking new avenues” for scientific investigations (NSF, 2006; p. 1; Hawkings, 1998; NRC, 2011; The National Academies, 2009).

Several educational agencies have advocated the instructional importance of complex systems ideas and perspective in science education since the 1990s (AAAS,
The American Association for the Advancement of Science calls for the teaching and learning of systems concepts and processes such as the notions that systemic changes occur over extended time scales, and that system properties can arise from the interactions of its parts (AAAS, 2009). Through the Benchmarks for Scientific Literacy, the Framework for K-12 Science Education and the recently published Next Generation Science Standards, scientists and science education researchers posit that it is necessary that students are familiar with crosscutting system concepts so as to provide the scientific perspective when interpreting systems which are complex (AAAS, 2009; NGSS, 2013; NRC, 2011; NSTA, 1998).

Leading complexity scientists from the New England Complex Systems Institute (NECSI, 2001) further explain that students need to be taught to develop a complex systems perspective because this perspective corresponds to the scientific and socio-scientific environment that they will face when they graduate. As Robert Goldstone succinctly contends in a commentary, “complex systems are powerful mental tools because they allow widespread prediction and induction… teaching complex systems is important because their predictions and inductions would not normally occur to people who are not exposed to them” (2006, p. 37). Indeed, research on teaching and learning about complex systems has achieved solid grounding as an important field (Hmelo-Silver & Kafai, 2011). Given the centrality of complex systems in modern science and in science education, the challenge of teaching the next generation about these systems and to perceive science through this perspective is of utmost significance.
1.3 Significance

Despite the standards and policy emphasis in complex systems for almost thirty years, considerable research has documented several difficulties that science students continue to face in understanding complex systems and the associated ideas (Booth-Sweeney & Sterman, 2007; Jacobson et al., 2011). For instance, biology students are unable to perceive relationships among components in complex food webs, ecological systems, and organ systems beyond direct cause-and-effect connections (Brown & Schwartz, 2009; Lin & Hu, 2003; Reiss & Tunnicliffe, 2001; Songer, Kelcey & Gotwals, 2009). Physics students view current in electric circuits as a sequential flow rather than as an emergent pattern resulting from the simultaneous interactions among electrons in the circuit (Perkins & Grotzer, 2005; Slotta & Chi, 2006). Chemistry students likewise tend to interpret chemical reactions as deliberate, rather than passive and random actions of certain particles (Taber & Garcia-Franco, 2010). Several studies also report that getting students to master thinking from a complex systems perspective has been inherently difficult to achieve (e.g., Booth-Sweeney & Sterman, 2007; Brown & Schwartz, 2009; Eilam, 2012; Grotzer & Bell-Baska, 2003; Liu & Lesniak, 2006). Collectively, these studies indicate that students’ limited understanding of complex systems remains an educational problem.

Researchers have suggested several reasons that may have contributed to this problem. Some believe that the linear and often disparate ways current science curricula are organized fall short of a coherent framework for understanding diverse complex systems (Goldstone, 2006; Sabelli, 2006; Senge et al., 2000). Others propose that only
few complex systems concepts are embodied in the learning resources and students’ educational experiences (Grotzer & Bell-Basca, 2003; Klopfer et al., 2009; Klopfer, Yoon & Um, 2005; Levy & Wilensky, 2009). The lack of engagement opportunities in these concepts limits their exposure to understanding such systems from a complex systems lens. It is therefore unsurprising that current efforts in addressing this problem have focused on promoting student learning of complex systems and the associated ideas through novel interventions such as agent-based modeling tools, simulations, participatory learning activities and systems-oriented curricula (Ben-Zvi Assaraf & Orion, 2010; Goh, Wong et al., 2013; Jacobson et al., 2011; Klopfer et al., 2009; Levy & Wilensky, 2011; Liu & Hmelo-Silver, 2009; Riess & Mischo, 2009; Yoon, 2008; Yoon, Klopfer et al., 2013).

Other researchers have also explored this educational problem of students’ limited complex systems understanding from the teacher perspective. These investigations include how science teachers interpret these systems (Ekborg, 2005; Hmelo-Silver & Pfeffer, 2004; Hmelo-Silver et al., 2007), what they understand about particular complex systems ideas (Booth-Sweeney & Sterman, 2007; Brown & Schwartz, 2009), how they represent complex systems to their students (Randler & Bogner, 2007; Vikstrom, 2008), and how they can learn about these systems (Klopfer, Yoon & Perry, 2005; Wilensky & Resnick, 1999). Generally, these studies have found that teachers too seem to lack an adequate understanding of complex systems, their learning challenges can be overcome with appropriate interventions, and their instructional practice can influence student learning of complex systems. Investigating this educational problem from a teacher angle
is imperative because it is well-established in the literature that what teachers know influence what and how they teach, and in turn may affect what and how students learn (e.g., Abell, 2007; Ball et al., 2008; Beausaert, Segers & Wiltink, 2013; Newton & Newton, 2001; Puntambekar, Stylianou & Goldstein, 2007; Sadler et al., 2013; Sanders, Borko, & Lockart, 1993). Indeed, numerous complex systems interventions studies involving teachers have implied that they are key elements in facilitating student learning (Azevedo et al., 2005; Castano, 2008; Grotzer & Bell-Baska, 2003; Riess & Mischo, 2010).

While the current studies emphasizing teachers’ understanding, learning and instruction of complex systems are worthwhile endeavors and have yielded various discoveries and successes, the teacher aspect is still somewhat under-researched in four aspects. First, all of the teacher-studies are limited in scale and representativeness, with the teacher samples selected from one or two schools or certain professional development programs (Hmelo-Silver et al., 2007; Klopfer et al., 2005; Wilensky & Resnick, 1999). Do the findings from these studies apply to a more general population of science teachers? Second, the studies that investigate teachers’ understanding look only at a few ideas of complex systems. For instance, in one of the more detailed studies of teachers’ conceptions of complex systems, Booth-Sweeney and Sterman (2007) considered their notions of feedback mechanisms, time delays, and non-linear causality; other equally salient ideas of complex systems such as emergence, self-organization, and decentralization regrettably have not been explored in this or other teacher-studies. Third, not much is known about what complex systems ideas teachers teach in regular science
classrooms. Do they convey these ideas at all? Additionally, teachers’ subject matter knowledge can influence the way they teach, but this has yet to be empirically investigated in the context of complex systems ideas. Does this relationship hold true for this domain? Fourth, while there are suggestions that teachers face difficulty in understanding and teaching complex systems, a systematic and empirical investigation of the reasons behind these difficulties from teachers’ points of view has not been done. Why do complex systems present challenges in understanding and teaching to teachers?

Taken collectively, these observations indicate clear gaps in the literature; there are still significant grounds to be made in terms of gaining comprehensive insights into the state of science teachers’ complex systems understanding and teaching. A central goal of this study is to inform professional development in complex systems. It is hoped that through this study, empirical evidence can be obtained to show that such professional development is imperative to enhance their capacities in teaching complex systems.

1.4 Research Questions

A more thorough investigation of science teachers’ understanding and teaching of complex systems is carried out in this study. This means the investigation not only attempts to find out what individual teachers know about complex systems, but also seeks to examine what complex systems ideas they teach, how their knowledge of complex systems may have influenced their instructional practice and why complex systems may be difficult for the teachers to comprehend and teach. The following research questions (RQs) are posed.

RQ 1: a) To what extent do science teachers understand complex systems ideas?
b) Are there complex systems ideas that are more difficult than others for science teachers to understand? If so, what are they?

These questions examine science teachers’ understanding of complex systems ideas. Findings to these questions illustrate the current state of complex systems understanding among our teachers and the relative difficulty of the complex systems ideas.

RQ 2: a) To what extent are complex systems ideas conveyed during science teachers’ instructional practices?

b) What is the relationship between science teachers’ understanding of complex systems and their instructional practices?

These questions explore what and how explicit complex systems ideas are conveyed during regular science instruction, and what relationship exists between teachers’ understanding and teaching of these ideas. Findings to these questions illustrate the state of complex systems instruction in regular science classrooms and ascertain the relationship between teacher understanding and instructional practice in the domain of complex systems.

RQ 3: What are science teachers’ reasons behind the perceived difficulties in understanding and teaching complex systems ideas?

The question explores why teachers may find difficulty in understanding and teaching complex systems ideas. Findings clarify the challenges and issues to be addressed in the push for complex systems instruction in science classrooms.
1.5 Chapter Summary

Researchers and policymakers have long advocated instruction of complex systems in school science. However, persistent student misconceptions in several complex systems-related concepts and phenomena mean that more can be done to address this educational problem. This research considers this problem from a teacher perspective by seeking to obtain a comprehensive and coherent picture of science teachers’ current state of complex systems understanding and instruction. It contributes to the emerging body of literature on learning and teaching complex systems in school science. More importantly, it advocates professional development for science teachers in this domain. The next chapter provides a review of the related literature and lays the foundation for the research’s conceptual framework.
2 LITERATURE REVIEW

2.1 Chapter Overview

This chapter is a review of the literature surrounding teacher understanding and the relationships between their understanding, and student learning and instructional practice. It is also a review of understanding complex systems in science. As this research lies at the intersection of several knowledge bases, the literature review chapter is split into three sections.

- Section 2.2 is a discussion on what an understanding of a subject matter constitutes, what the relationships between teacher understanding and student learning, and between teacher understanding and instructional practices are. This section explains the rationale of examining the educational problem of limited students’ awareness in complex systems from a teacher perspective and argues for concurrent investigations of teacher knowledge and instructional practice.

- Section 2.3 provides a description of complex systems and contains a critical review of the literature on teaching and learning complex systems in school science. The former aims to familiarize readers with the operational definitions for this study, while the latter seeks to identify and clarify the research gaps briefly stated in the introductory section 1.3.
Section 2.4 puts together the arguments from the earlier two sections to support an empirical investigation of teachers’ understanding and teaching of complex systems. Specifically, it conceptualizes and justifies a framework for this study.

2.2 Teacher Understanding

Teachers’ understanding of complex systems is a focus of this study. Drawing from the teacher knowledge literature, this section begins with an elaboration of teacher knowledge to describe what it means by understanding a subject matter. A discussion on the relationship between teacher understanding and student learning and between teacher understanding and instructional practice then ensues. This is to elucidate the research’s central argument that in order to make sense of students’ limited awareness of the complex systems ideas, it is necessary to examine teachers’ own understanding of the subject matter and their instructional practices.

2.2.1 Understanding a subject matter

A review of teacher knowledge is not a simple task. This is because teacher knowledge is multi-faceted (Abell, 2007; McDiarmid & Clevenger-Bright, 2008). In one of more influential research programs, Shulman and his associates (1987; Grossman, Wilson & Shulman, 1989) identified at least seven knowledge bases – subject matter knowledge, pedagogical content knowledge, pedagogical knowledge, curricular knowledge, knowledge of students, knowledge of context, and knowledge of educational goals – that teachers need to draw from in order to teach effectively. Of these knowledge bases, subject matter knowledge and pedagogical content knowledge are intricately linked to teachers’ understanding of the subject matter or content, whereas the remaining
five pertain less to the subject matter *per se* but other domain-general aspects of teaching such as learning styles, classroom learning environment, instructional strategies, and classroom management skills. These bases make up the plethora of knowledge teachers need for teaching well. It is therefore necessary to define exactly the aspect of teacher knowledge this study is interested in.

An understanding of the complex systems content can be best described as a form of science subject matter knowledge. However, science subject matter knowledge itself also defies a narrow definition. Influenced by Schwabs’ earlier works of syntactic and substantive knowledge (Schwabs, 1964, as cited in Ben-Peretz, 2011), science education researchers have clarified that to think properly about the science subject matter requires going beyond facts and concepts of the domain – substantive knowledge – to include an understanding of how claims of the facts and concepts are validated and justified – syntactic knowledge (Crawford, 2007; Gadgil, Nokes-Malach & Chi, 2012; Gess-Newsome, 1999; Hayes, Capel & Katene, 2008; Herrington et al., 2011; Smith & Siegel, 2004; Voss, Kunter & Baumert, 2011). In other words, science subject matter knowledge is about understanding of the key ideas of the science content, its logical structure, the various ways of defining and analyzing in the subject, and the standards of judgment and evidence that operate in the field. Some researchers also include perceptions about the subject matter, or conceptual beliefs, into the definition of subject matter knowledge (Abell, 2007; Coburn, 2000; Luft et al., 2003; Southerland, Sinatra, & Matthews, 2001). Conceptual beliefs refer to a kind of personal knowledge to explain the phenomena in
question, one that is subjective and non-evidential, and relies on personal observation and judgment.

Acknowledging the inherent complexities in examining teachers’ subject matter knowledge, this research leans towards explicating the extent to which science teachers are aware of the central ideas of complex systems. It does not examine their technical fluency in defining and articulating these ideas, nor in describing the syntactic aspects of this field. It also does not attempt to differentiate between their perceptions about complex systems and their actual scientific knowledge of the field. The reason for setting up such an expansive boundary is because, being a domain of ideas which has gained prominence in science education only in the past decade (Jacobson & Wilensky, 2006; NGSS, 2013), it can be reasonably assumed – and indeed this research has proven this to be so – that most science teachers have little prior exposure to complex systems. For the purpose of this study, the term ‘understanding complex systems’ is hereafter adopted to reflect this less-than-formal sense-making of the domain, encompassing teachers’ subject matter knowledge and conceptual beliefs of the central complex systems ideas.

2.2.2 Relationship between teacher understanding and student learning

How does an investigation of teacher understanding of complex systems help in addressing the educational problem of students’ limited awareness of this domain? This section discusses the relationship between teacher understanding and student learning.

The literature is replete with studies which demonstrate a relationship between what teachers know and what students learn. Generally, teachers who do not have an adequate understanding of the subject matter can misrepresent the content to their students, causing
them to have misunderstanding (Ball et al., 2008; Ball & McDiarmid, 1990; Diakidoy & Iordanou, 2003). One area of research that sheds light on this relationship comes from the field of scientific misconceptions. Studies have surfaced parallel misconceptions among students and teachers, suggesting a link between teachers’ understanding and student learning. In physics for example, the misconception that gamma radiation is most penetrating due to its high energy as compared to alpha and beta particles without referencing their relative ionizing properties with their environment, has been observed in high school and college students (Alsop & Watts, 2000; Henriksen & Jorde, 2001; Prather & Harrington, 2001; Rego & Peralta, 2006), and teachers (Aubrecht & Torick, 2001; Colclough, Lock & Soares, 2011). Other misconceptions such as current flow in physics (Liegeois & Mullet, 2002; Perkins & Grotzer, 2005; Pratim & Wilensky, 2009; Singh, 2010), evolution and photosynthesis in biology (Ahopelto et al., 2011; Garvin-Doxas & Klymkowsky, 2008; Kalinowski, Leonard & Andrews, 2010; Storey, 1989), and gravity, magnetism, gases, and temperature at the elementary levels (Burgoon et al., 2010; Kruger, Summers & Palatio, 1990; Tatar, 2011) have also been documented in students and teachers. These various studies suggest that there is a relationship between teacher and student understanding in science.

The relationship between teacher understanding and student learning has also been investigated in a more direct manner. In a randomized experiment involving over 270 elementary teachers and 7,000 students, Heller and her colleagues (2012) attempted to identify links between teacher knowledge and student achievement. They compared three related but systematically varied teacher interventions along with no-treatment
control. They found that teacher gains in subject matter knowledge significantly predicted student gains on science tests, but they also acknowledged that it was not possible to account for all influences on student learning. On a smaller scale, Kanter and Konstantopoulos (2010) studied the impact of a professional development program of a project-based science curriculum on minority student achievement. They too discovered that the average subject matter knowledge of the nine teacher-participants in their study were predictors of their student achievement in the same topics. Similarly, in d’Apollonia and her team’s (2004) study with two classes of biology college students where the experimental class was introduced to the concepts of complex systems before evolution, and the control class was only taught evolution concepts, they found striking similarities between the students’ and their teachers’ mental conceptions of evolution. They suggest that this somewhat reflects the powerful impact that teachers’ mental models have on student learning.

Although science education researchers generally agree that teacher understanding of the content plays an important role in student learning, many also acknowledge that the relationship is not as clear-cut. There are other factors such as the enacted curriculum, the instructional practices, teachers’ pedagogical content knowledge and sociocultural factors mitigating the impact on student learning (Anderson & Clark, 2012; Beausaert, Segers & Wiltink, 2013; Bowen, 2000; Darling-Hammond, 2000; Metzler & Woessmann, 2012; Monk & King, 1997; Puntambekar, Stylianou & Goldstein, 2007; Roth et al., 2011; Rowan, Correnti & Miller, 2002). One of these factors – instructional practices – is discussed in the next section.
2.2.3 Relationship between teacher understanding and instructional practice

In the earlier section, it describes that what teachers understand about the subject matter can impact student learning, but this relationship can be mitigated by their instructional practices (Darling-Hammond, 2000; Monk & King, 1997; OECD, 2011). There are many aspects of instructional practice that researchers have examined and these include, among others, organizational features, instructional strategies, engagement levels, classroom discourse and roles of teachers and students (e.g., Furberg & Arnseth, 2009; OECD, 2011; Singer et al., 2011; Thandani, Stevens & Tao, 2009; Treagust, Duit, Joslin & Lindauer, 1992; van der Zande et al., 2011). This review section focuses on the content aspect of instructional practice, in particular the relationship between what teachers understand and what they teach. An appreciation of this particular relationship between their understanding and their teaching may help make sense of the educational problem of students’ limited complex systems understanding.

In a comprehensive review of the research on science teacher knowledge, Abell (2007) concludes that there is substantial evidence in the literature to suggest a positive relationship between science teachers’ subject matter knowledge and their science teaching. Overwhelmingly, it is found that when science teachers possess the necessary content expertise, they are better able to communicate the concepts and ideas and skillfully engage students in the content (e.g., Ball et al., 2008; Brickhouse, 1990; Darling-Hammond, 2000; Gess-Newsome, 1999; Gess-Newsome & Lederman, 1995; Heller, Daehler & Shinohara, 2003; McDiarmid & Clevenger-Bright, 2008; Nehm & Schonfeld, 2007; Sanders, Borko & Lockard, 1993). For instance, Childs and McNicholls
(2007) analyzed videos of an experienced high school chemistry teacher’s explanatory discourse when teaching the concepts of energy transfer. They observed that when the teacher was teaching within her content specialization in chemistry such as when she was teaching about energy transfer by conduction and convection, she was better able to match the content of her explanation with the teaching purpose of the explanation episode by offering analogies and stories that were not reflected in the textbook. In contrast, when she was unable to draw upon her own domain of chemistry such as when she was teaching about energy transfer by radiation, she appeared to be less effective at aligning her scientific explanation with the learning goal and stuck closely to the textbook.

Likewise, Rollnick and his collaborators (2008) found that when their case study teachers lacked the subject matter knowledge on molar concept and chemical equilibrium, they resorted to a strict reliance on algorithms during problem-solving and displayed inflexibility in their teaching; traits that Gess-Newsome (1999) identified as novice characteristics. The only teacher who had a nuanced understanding of that topic exhibited the flexibility to produce varied approaches and a range of explanations in his teaching. Dawkins and her team (2008) also discovered that because their target sample of seven pre-service student teachers did not possess an adequate and coherent conception about density, especially in the form of a mathematical relationship of mass and volume, this affected the way they prepared their lessons for the topic and subsequent ones as well. The teachers even appeared to have inconsistent explanations of density. Several other studies also show relationships between content understanding and teacher practice across science domains and grade levels (e.g., Abd-El-Khalick, 2006; Harlen &
Besides being more competent in communicating the scientific concepts explicitly, some studies also suggest that science teachers with the necessary subject matter understanding can influence how these concepts are conveyed implicitly through other related topics. Observing the instructional practice of three case study teachers, Brickhouse (1990) noted that their beliefs about the nature of science both influenced explicit lessons of the topic and shaped an implicit curriculum concerning the nature of scientific knowledge. Her teachers conveyed their own conceptions about the nature of science through their instruction of other topics. This is similar to what Lederman (1999) found in his study with five high school biology teachers. He reported that while some teachers were found to have used pedagogies consistent with the nature of science, these teachers insisted that they were not explicitly trying to do so and did not claim to be trying to improve students’ understanding of the nature of science. These findings support the notion that teachers may convey certain ideas during their instruction due to the influence of their subject matter understanding, even though the lessons are not directly related to the particular subject matter.

There are, however, a few findings that have pointed to the contrary – what teachers know may not necessarily be translated into their teaching. In the same study mentioned in the prior paragraph, Lederman (1999) noted that teachers’ conceptions of the nature of science did not always influence classroom practice. He found that a small
number of teachers did not teach in a manner consistent with their views of the nature of science. Mellado and his colleagues (2008) too discovered that even though their case study teacher had a constructivist orientation in learning and teaching, she followed a strategy of direct transmission of knowledge based exclusively on teacher explanations. This non-unanimous conclusion requires that the relationship between teacher understanding and instructional practice be investigated in the domain of complex systems. Establishing this relationship will lend support to the study’s goal of advocating professional development in complex systems.

2.3 Understanding and Teaching Complex Systems

Having clarified what understanding of a subject matter entails, explained the relationship between teacher understanding and student learning, and the relationship between teacher understanding and instructional practices, this section now illustrates what constitutes an understanding of complex systems. Salient ideas related to complex systems and conceptual difficulties related to these ideas are described. Reasons that may have caused difficulties in understanding and teaching complex systems are also discussed.

2.3.1 Salient complex systems ideas

A system is complex when the elements or parts that make up the system are interconnected and communicate in multiple, nonlinear ways (Mitchell, 2009; Yoon, 2011). The patterns of interactions form a collective network of relationships that exhibit emergent properties that are not observable at subsystem levels (Penner, 2000; Resnick, 1994; Yoon, 2008). When perturbations occur, the network self-organizes, often in
unpredictable ways, and new properties can emerge without a centralized or intended design (Bar-Yam, 1997; Jacobson, 2001; Jacobson et al., 2011). To have an understanding of complex systems, one needs to look at the ways the system and its components interact with one another and with the environment, respond to perturbations, and self-organize by studying the dynamic processes through which they evolve over time (Goh, Yoon et al., 2011; Jacobson et al., 2011; Yoon, 2011).

Pavard and Dugdale (2000) summarize four sets of ideas or properties that appear to be generally applicable to a variety of complex systems. Their framework is adapted as an organizing map to illustrate some salient complexity ideas inherent in several scientific domains. It is appropriate at this point to recognize that there are no “tidy descriptions and unambiguous definitions” of complex systems (Davis & Sumara, 2006, p. ix). Many researchers in their attempts to come up with a list of characteristics, processes, or ontologies depicting complex systems caution the problematic nature of this task (Garnsey & McGlade, 2006; Jacobson et al., 2011). Nonetheless, by drawing upon seminal literature of early complex systems researchers (e.g., Bak, 1999; Capra, 1996; Kauffman, 1995; Prigogine & Stenger, 1984) and recent reviews of the topic (e.g., Davis & Sumara, 2006; Lesh, 2006; Mitchell, 2009), the non-exhaustive framework attempts to embrace the diversity in this field.

2.3.1.1 Non-determinism and nonlinearity

Complex systems are non-deterministic, that is, it is difficult to anticipate precisely the properties of such systems even if the behaviors of their components are known (Prigogine & Stenger, 1984; Lewin, 1999). This difficulty stems from the fact that
the components affecting the system operate through complex feedback and causal mechanisms. These mechanisms interconnect the components in multiple nonlinear ways, which in turn make prediction of cause-and-effect(s) difficult (Garnsey & McGlade, 2006; Kauffman, 1995). For example, the plants, animals, and other abiotic elements that make up an ecosystem are so intricately connected to one other that it is complicated to predict how an ecosystem will respond after a perturbation such as an extinction of a certain insect species due to the use of a pesticide (Bar-Yam, 1997).

2.3.1.2 Open and dynamic nature

Complex systems are open and dynamic in nature (Kauffman, 1993; 1995). Being open or ambiguously bounded, complex systems allow the inflow and outflow of information, matter and energy through the boundaries of the systems (Davis & Sumara, 2006). Researchers argue that it is this permeability facilitating the continuous exchange of materials with the environment that enables these systems to be dynamic (Bar-Yam, 1997; Gell-Mann, 1995). The term ‘dynamic’ means that there is no apparent beginning, middle and end to the processes underlying the complex systems (Jacobson, 2001). Understanding this open and dynamic nature of complex systems is often problematic as it requires one to perceive a system beyond its natural spatial and temporal boundaries to include the surrounding environment and an extended timescale (Booth-Sweeney & Sterman, 2006; Mitchell, 2009). For instance, to fully comprehend the processes driving the earth’s water system, one has to consider the continual process of the Sun’s input, heat loss to space, and conversion to energy in living organisms over a long period of time (Ben-Zvi Assaraf & Orion, 2005).
2.3.1.3 Emergence and self-organization

Scientists have shown that each component in complex systems acts in accordance to a set of behavioral and interactional rules, and that it is the collective enactment of these rules that self-organizes into emergent characteristics at the system level (Corning, 2002; Sawyer, 2005). Emergence refers to the phenomenon where the complex entity manifests properties that exceed the summed traits and capacities of individual components (Davis & Sumara, 2006). In other words, the patterns that occur at the system level ‘emerge’ from the simpler interactions among the components (Capra, 1996; Lesh, 2006). Closely related is the idea of self-organization, which refers to the spontaneity of this emergence (Bak, 1999). Self-organization is in opposition to the notion of organization by deliberate design, which is most people’s intuitive understanding about systemic patterns (Bar-Yam, 1997; Kauffman, 1995). Take for instance the behaviors of slime mold cells. Scientists believe that the process where individual mold cells come together to form an aggregate structure in the absence of food and disperse again when there is abundant food, is the emergent, self-organizing result of simple chemical interactions among the cells in response to the environment. That is, the aggregation-dispersal phenomenon is not the result of a deliberate behavior encoded within each cell, as it has been widely believed (Resnick, 1994).

2.3.1.4 Decentralization

Decentralization is the idea that the specific characteristics and order of a complex system cannot be precisely localized to one component or a part of the system (Davis & Sumara, 2006; Kelso, 1995), and these systemic characteristics and order can be
attributed to the interrelationships or multiple connections that exist among the components (Bar-Yam, 1997). The idea of decentralization is somewhat related those of emergence and self-organization, except that the former focuses on the collective influence of the components over a system, while emergence and self-organization refer to the outcomes of the influence. For instance, the seemingly organized way birds fly in a formation is found to be the result of localized interactions at the individual level, and not of a centralized control, say the leader bird at the head of the flock (Resnick, 1994). However, the order that these natural complex systems display is often intuitively interpreted to be only possible through centralized control imposed from within or outside the system (Chi, 2005; Jacobson, 2001).

These ideas describing the nature of complex systems have been synthesized from writings of complexity in multiple scientific domains. By proxy of their commonalities, it is likely that they are among the most salient to be understood in the field (Waldrop, 1992). Seen in this light, teachers’ understanding of this field can be delineated into their knowledge and conceptual beliefs of these four complex systems ideas – nonlinearity and non-determinism; open and dynamic nature; emergence and self-organization; and decentralization. These ideas have proven to be counter-intuitive or even in conflict with commonly held beliefs, posing challenges in understanding and teaching for both teachers and students alike (Casti, 1994; Chi, 2005; Jacobson, 2001). What are these challenges? The next section discusses them.
2.3.2 Difficulties in understanding complex systems

Challenges associated with the understanding of these complex systems ideas are examined in this section. An appreciation of these challenges helps justify the educational problem, identify gaps in the literature and inform next steps in research. This research focuses on teachers, but a review of the literature uncovers only a handful of studies that looks at this target group in particular. In order to provide more insight into what teachers know about the nature of complex systems, findings from studies examining students’ and young adults’ understanding and learning are also included. Such studies are relevant because, as described earlier in section 2.2.2, the literature suggests a relationship between student learning and teachers’ subject matter understanding.

2.3.2.1 Linear and deterministic thinking about relationships

One salient idea of complex systems described earlier is their nonlinear relationships among the components, and the unpredictability of the consequences arising from perturbations in the system. Only a handful of studies examine teachers’ perceptions of the relationships of components, and of processes in complex systems (Booth-Sweeney & Sterman, 2007; Hmelo-Silver et al., 2007); studies involving students and young adults are also reviewed in this section (Ben-Zvi Assaraf & Orion, 2010; Eilam, 2012; Green, 1997; Grotzer & Bell-Basca, 2003; Hogan, 2000; Lin & Hu, 2003; Perkins & Grotzer, 2005; Plate, 2010; Raia, 2005; Schizas, Katrana & Stamou, 2013; White, 1997). This is justified due to a possible connection between student learning and teacher understanding. Generally, the findings show that people tend to perceive the relationships
and processes in complex systems linearly, limit these relationships and processes to direct cause-and-effect connections, and view the effects as mostly predictable.

In a food web study with 52 6th graders, Hogan (2000) observed that the students traced food web perturbations primarily as one-way linear flow, rather than as two-way or cyclic flow. Hogan noted that during a food web analysis task where they were asked to draw and explain the effects when changes occur to a part of their food web, the students had a strong tendency to think of unidirectional change when one population was affected. Even for the small number of students who could identify cyclic patterns (e.g., producer to consumer to decomposer and back to producer), he found that they had limited recognition of feedback, which is a key nonlinear process of complex systems. The students also possessed a view of the consequences as certain and inevitable. In an intervention study involving over 300 middle school students, Gotwals and Songer (2010) also concluded that students encountered difficulties in analyzing the subsequent effects on a food web when a part of it was perturbed. This difficulty was especially pronounced when the populations were not directly linked in a predator-prey relationship.

Students’ inability to deal with the nonlinearity of complex systems is not limited to their interpretation of the multiple interactions between the system components. Other studies have demonstrated that comprehending the relationships in the concepts underlying these systems is just as challenging (Ben-Zvi Assaraf & Orion, 2005; Eilam, 2004; Lin & Hu, 2003; Wu, 2010). In a study involving multiple cases, Parnafes (2010) examined how high school physics students made sense of the natural harmonic motions of oscillating systems. When asked to explain how “fast” an oscillator is, all 8 pairs of
students in the study were drawn by various aspects of motion, and inferred an “overall and non-specific impression of fastness” (p. 574). They were confused by the various concepts of motion (e.g., speed, frequency, and period), and could not elicit the relationships among them. Difficulty with this epistemological complexity (Levrini et al., 2006) or conceptual complexity (Fortuin, van Koppen & Leemans, 2011), is evident even among undergraduate students. They too struggled with multiple connections among various concepts and processes, and preferred a simplified view of complex systems where the outcomes were more predictable (Blikstein & Wilensky, 2009; Jensen & Brehmer, 2003).

A few small-scale studies have assessed science teachers’ understanding, and they too show that interpreting the nonlinearity in complex systems poses similar problems for teachers. For example, Hmelo-Silver and her colleagues (2004; 2007) exposed the shortfalls in the responses of two small groups of pre-service science teachers who were asked to describe respiratory or aquarium systems. While the teachers generally could identify with ease the components or structures in these complex systems, they neglected the functions and behaviors of the components in relation to other components in the same system. The researchers explained that their inability or inattentiveness in highlighting the interconnectedness espoused by the functions and behaviors demonstrated a novice-like understanding of complex systems. Likewise in a study involving middle school students and 11 teachers from two schools, Booth-Sweeney and Sterman (2007) noticed that while the teachers generally outperformed the students in pointing out the interconnectivity among components in a scenario on population system,
half of the teachers failed to mention nonlinear feedback loops that can affect population growth.

In short, these studies largely establish that students and teachers have limited understanding of the nonlinear and non-deterministic interactions among system components, and of the interconnectedness and relationships of various concepts underlying complex systems. However, the studies involving teachers are small-scale and employ teacher samples from one or two selected schools or professional development programs, restricting the generalizability of the claims. It is therefore necessary to conduct larger-scale studies in order to better ascertain the extent of science teachers’ understanding of nonlinearity and non-determinism.

2.3.2.2 Inability to see beyond immediate components, system, and time

The second common property relates to the open and dynamic nature of complex systems. Only one study looks at how teachers recognize the time-related dimension of complex systems (Booth-Sweeney & Sterman, 2007), therefore those studies that explore how students perceive systems beyond their natural spatial and temporal boundaries (Ben-Zvi Assaraf & Orion, 2005; Eilam, 2012; Kali, Orion & Eylon, 2003; Wilson et al., 2006) are also reviewed. This is justified due to a likely relationship between student learning and teacher understanding. Collectively, the findings reveal that individuals generally neglect the interactions between systems, perceive them to be isolated and static, and overlook the impact of time delays.

In a study of a group of 40 7th grade students from a single school, Kali, Orion and Eylon (2003) assessed what they knew about the rock cycle, and the geological and
atmospheric processes underlying the dynamic nature of rock transformation. While the rock cycle is really a system that includes rocks exposed on the surface of the earth, those within the crust of the earth and those melted as magma in the upper mantle, the researchers explained that the students focused only the more visible rocks on the surface, limiting their perceptions of this earth-based system. Most of the students also described rocks as static features, that is, the rocks interact minimally with other components (e.g., wind, water, and heat) and undergo little transformation.

In another study with 50 8th grade students, Ben-Zvi Assaraf and Orion (2005) concluded that their students were unable to deal with the open nature of the complex water cycle system. The students mainly discussed processes involving the more-noticeable atmospheric and groundwater components, such as water vapor, rain, snow, clouds and rivers of the water cycle. They neglected processes associated with less-obvious components (e.g., water retained in the soil), and the biotic system (e.g., water uptake from plants and animals). In other words, the students could only recognize the more visible subset of the hydro-system, and failed to see how it is connected to other hidden components and systems. Likewise, in a study with undergraduate biology students, Wilson and his colleagues (2006) shared that their participants found it challenging to trace matter from one complex biological system to another.

There is only one study that examines how teachers understand the ideas of open and dynamic nature. Booth-Sweeney and Sterman (2007) reported that most of their 11 teacher-participants in two schools had trouble interpreting the operations of natural complex systems (e.g., predator-and-prey system, population system) when the causes
and effects are distant in time and space. Most of the teachers did not consider the
timescales over which changes may occur, and as a result, neglected their dynamic
nature. In addition, two common misconceptions regarding the flow of materials into or
out of systems were found. Although the stock, that is the amount of system components,
is dependable on both inflow and outflow, more than half of their teacher-participants
either focused solely on the inflow to the system (e.g., population gets bigger because of
births) or mistakenly assumed that the inflow equals to the outflow (e.g., population stays
the same because each day a baby is born and each day somebody dies).

These studies demonstrate that teachers and students possess difficulties
interpreting the open and dynamic nature of complex systems. Restraining the
perceptions of systems within their more visible spatial and temporal boundaries, they
seldom consider the less obvious but nonetheless key components of the system. They
also do not acknowledge the relationships among systems, nor recognize that various
changes to the system can occur over different timescales. Unfortunately, the only teacher
study that looks at the ideas of open and dynamic nature involves only 11 teacher-
participants (Booth-Sweeney & Sterman, 2007); larger-scale research is needed to
determine the extent teachers understand these complex systems ideas. While the student
studies may offer some hints into teachers’ understanding of open and dynamic nature,
more teacher studies are required to find out their current state of understanding.

2.3.2.3 Intentional design and confusion of levels

The other major ideas of complex systems relates to emergence and self-
organization. There is only one study that examines teachers’ understanding of
emergence and self-organization, so studies investigating student understanding of these ideas are also reviewed to provide clues on what can be expected for teachers. This is acceptable as due to a possible connection between student learning and teacher understanding. Generally, researchers have found that understanding these properties can be counter-intuitive. Students and teachers are seen to perceive patterns at the system level to be deliberately produced with a purpose or function in mind, as opposed to being self-organized and emergent (Brown & Schwartz, 2009; Garvin-Doxas & Klymkowsky, 2008; Liu & Lesniak, 2006; Taber & Garcia-Franco, 2010; Treagust, Chittleborough & Mamiala, 2003; Wilensky & Resnick, 1999).

When Taber and Garcia-Franco (2010) interviewed 55 secondary school chemistry students on their understanding of the macroscopic properties of matter and the submicroscopic behaviors of particles, they found that the students naturally viewed macroscopic chemical complex reactions as deliberate acts at the particulate level. The students believed that active agents are needed for a chemical reaction to begin because “particles do not move on their own” (p. 118), and that when substances interact, one of the substances is considered more responsible or viewed as a more active partner in causing the change. In addition, the students recognized the macroscopic properties of matter as simply reflective of the sum of the component behaviors. For instance, they mentioned that the cloudiness in a mixture containing silver ions is a direct result of the silver metal present in the solution. In another study involving 54 Grades 1 to 10 students, Liu and Lesniak (2006) noted that most were unable to relate macroscopic observations to submicroscopic explanations. For example, mixing of baking soda and
water was generally seen as ‘dissolving’ rather than forming a new substance. They were unable to recognize that similar submicroscopic processes may give rise to different macroscopic properties.

Such misinterpretation of the patterns observed at the system level is also detected in the biology and physics context. Garvin-Doxas and Klymkowsky (2008) noticed that their biology college students possessed the notion that biological processes are intentionally designed for efficiency, with certain drivers controlling these processes. For example, mutational processes occur only in response to natural selection pressures. The reasoning that random alterations at the cellular level take place all the time and can give rise to complex and often counterintuitive behaviors at a more macro-scale was almost totally absent in these young adults. In another study, Perkins and Grotzer (2005) examined 72 elementary school students’ understanding of electrical circuits. Analyses of their interviews and responses in a concept test revealed that the students typically tried to analyze electrical effects sequentially, using what the researchers call a “sequential causal pattern” for how the current flows (p. 130). The students envisioned current flow as a linear process, traveling from point to point, and affecting each circuit component in turn as it is encountered within the circuit. However, current flow is in fact a simultaneous, emergent pattern arising from the localized interactions of electrons throughout the circuit.

While the literature has been rather conclusive about students’ limited awareness of self-organization and emergence in complex systems, the review has found only one teacher study that looks at these ideas. It also portrays a similar state of understanding for
the teachers. In a study of biology pre-service teachers’ understanding of photosynthesis and cellular respiratory systems, Brown and Schwartz (2009) reported that their 18 teachers were limited in their understanding of the photosynthesis and respiratory processes impacting multiple ecological levels. Their teachers could explain the processes well and affirm that the photosynthesis and respiration are connected. However they lacked a systems view that traces and connects these processes across multiple levels. The teachers seldom articulated the biochemical and cellular levels of these processes and struggled to conceptualize how the reactants and products of photosynthesis and respiration are related at the organism, local and global level.

In short, it is clear that students and pre-service teachers experience difficulty in interpreting systemic patterns as arising non-intentionally from localized interactions at the component level. These studies which involve physical, chemical, and biological systems show that the ideas of emergence and self-organization are not easily perceived, and this causes prevalent misunderstanding of why and how certain complex systems phenomena occur. Disappointingly, the review only manages to find one study that assesses teachers’ understanding of the complex systems ideas of emergence and self-organization; more teacher studies are required to ascertain their current state of understanding.

2.3.2.4 Centralized control

Another major idea of complex systems is decentralization. Resnick (1996) comes up with the term “centralized mindset” to describe how people generally interpret the order of a complex system. No study involving teachers is uncovered, so this section
mainly reviews what the literature says about student learning and understanding of decentralization.

Researchers have generally discovered that students misconstrue the functions and operations of complex systems to be controlled by a certain component or variable in the system (Klopfer, Yoon, & Um, 2005; Klopfer et al., 2009; Papaevripidou, Constantinou, & Zacharia, 2007; Resnick & Wilensky, 1998; Wilensky & Reisman, 2006; Wilensky & Resnick, 1999). In Wilensky and Resnick’s (1999) case studies of students who participated in computational programming of natural phenomena (e.g., slime mold cells, gas particles in a box, and predator-prey in a community), the researchers noticed that students thought of the components in the complex systems in a “organization-chart” perspective. For example, in modeling the aggregation of slime mold cells, their students programmed certain cells to be “leaders” who instructed other cells to come together (p. 9). However, the aggregation pattern is actually an emergent property at the macroscopic level. There are no leaders involved, as the patterns simply surface from the localized rules that determine the behavior of each cell. In this case, each cell is believed to wander around randomly, and upon encounter with the pheromone scent left behind by another cell, it follows the scent in the direction of increasing concentration. When a number of cells follow this set of simple rules, an aggregation pattern emerges. Simply put, the students were perceived the component behaviors to be centrally determined by certain lead components.

This ‘centralized mindset’ finding is echoed in other studies involving students’ modeling of complex systems. For instance, Papaevripidou and his colleagues (2007)
discovered that in the initial stage of their research project on modeling marine ecosystems, their students focused on a few variables and interactions that appear to underpin the models, and arrived at simplistic notions of the controlling influence of these variables. Klopfer and his colleagues (2005; 2009) reported that during students’ early involvement in complex systems modeling in the “Adventures in Modeling” and “StarLogo TNG” curricula, the participants had to be guided to develop a more encompassing perspective in looking at the modeled phenomena. In comparing the cognitive differences between complexity experts and novices (i.e., undergraduates), Jacobson (2001) also presented telling evidence that the undergraduates he surveyed predominantly possessed centralized beliefs about complex social and natural systems, while the experts generally had decentralized beliefs.

To sum, studies have concluded that students generally adopt a centralized approach when interpreting complex system. That is, they have a restricted view of what controls a system as they are often seen to map its components and variables onto a hierarchy and ascribe influential properties to them in relation to their control on the system’s behaviors. However, no empirical research involving teachers has been uncovered.

2.3.2.5 Relative difficulties of complex systems ideas

From the review thus far, it appears that complex systems ideas are not intuitively easy to grasp – at least among students and small populations of teachers. Of these various ideas, are there ones that present more difficulty in comprehension? Are there specific complex systems ideas that are more problematic to conceptualize and
understand? Such questions are important because the answers can help focus instruction and learning of complex systems ideas.

Only one study has been uncovered from a review of the literature. The study is part of a National Science Foundation-funded project “DRK12-BioGraph: Graphical Programming for Constructing Complex Systems Understanding in Biology,” which I participated from 2010 to 2011 (Goh, Yoon et al., 2012; Yoon, Klopfer et al., 2013; Yoon, Koehler et al., 2014). In this project, a biology curriculum, grounded in complex systems ideas, is developed and tested. This novel curriculum structures biology content with complex systems ideas in mind, and incorporates computational modeling tools and other pedagogical resources to facilitate student learning. As a part of the project, we discovered an apparent hierarchy of difficulty of the complex systems ideas (Goh, Yoon et al., 2012). By coding and analyzing high school students’ written responses to a complex systems-based biology question concerning the effects on a park ecosystem due to the arrival of a population of geese, we found that the easiest complex systems ideas to articulate are those that relate to the interconnectedness of these systems whereas the most difficult ideas to grasp are those concerning the decentralized organization of the system, and the non-deterministic nature of the system effects.

The research may have provided some insights into the relative conceptual difficulties of complex systems ideas. However, it falls short in three areas. First, as acknowledged in the study, it employed a small sample set of 44 students, self-selected from a few schools. To further validate the claims, it needs to expand on its sample size and representativeness. Second, the relative difficulty of the ideas is inferred by
examining students’ responses to a single ecology question. It is possible that the question posed in the study may not adequately allow expression of all complex systems ideas equally, therefore biasing the results. The research team opines that separate assessment or another question set in a different context is needed to corroborate the findings. Third, and perhaps the most relevant to this current research context, high school students were the target population in that study. How these ideas are differentially interpreted by science teachers require a separate investigation altogether.

2.3.3 Teaching complex systems

Earlier in section 2.2.3, it has been established that it is also important to look at teachers’ instructional practices, besides what they know, in understanding the educational problem of students’ limited awareness in complex systems. This section is a review of the literature on teaching complex systems in school science.

Several studies have examined the development of instructional resources, curricula and strategies aimed at facilitating teaching of complex systems and most have reported successes to varying degrees (e.g., d’Apollonia et al., 2004; Bravo-Torija & Jimenez-Aleixandre, 2012; Klopfer, Yoon & Um, 2005; Levy & Wilensky, 2009; Randler & Bogner, 2009; Yoon, 2008; Yoon et al., 2013). Some researchers describe the efficacy of teaching and learning systems from a complex systems approach. For instance, Yoon (2008) illustrated how an instructional heuristic based on a complex systems evolutionary approach to harness the complexity inherent in the learning system of the classroom improved student knowledge of a complex socio-scientific issue. This approach requires the teacher to facilitate through individual and group activities.
involving opinion-forming, argumentation, risks-benefits assessment, group negotiation and sharing of opinions on genetic engineering dilemmas. She demonstrated that student rationales concerning the complex issue showed increases in their understanding of complex systems ideas over time. In another study on river ecosystem, Hoffer and her team (2011) introduced a computer simulation program *SimRiver* which allowed students to develop a river basin as a complex system with numerous variables. With the help of a teacher, the students were able to identify human activities affecting producers in the ecosystem. The researchers contested that through this teacher-facilitated simulation, the students developed a skill set for understanding nonlinear problems where the relationships involved were not simple cause-and-effect.

Other researchers talk about the various strategies involving the use of computer technologies that can be used to teach complex scientific systems. For example, Greene & Azevedo (2009) detailed how their middle and high school students acquired a sophisticated mental model of a complex biological system in a hypermedia learning environment when their teachers guided their self-regulated learning through planning and monitoring of strategies, and handling of task difficulty and demands. In another study involving an agent-based modeling program, *NetLogo*, to model the micro-rules underlying the phenomena of wolf-sheep predation and synchronized flashing of fireflies, Wilensky and Reisman (2006) described how teachers guided students in the investigation of the connections between different biological levels and observation of the resultant aggregate dynamics of such systems. More recently, Yoon, Klopfer and team (2013) also described how their intervention of using *StarLogo TNG* – an agent-
based modeling program – and other cognitively-rich activities might have helped in improving their teacher-participants’ instruction in biological complex systems. Another research team even looked at a college teacher’s use of a course wiki to harness the self-organized learning dynamics of young adults to learn about complex systems (May, Burgard & Abbasi, 2010).

Instructional strategies that use less technological tools to improve student learning of complex systems have also been developed and tested. For instance, Reinfried, Aeschbacher and Rottermann (2012) investigated a curricular unit of the complex concept of greenhouse effect, and illustrated how active and engaged learning could be promoted with instructional activities to facilitate deep conceptual understanding of greenhouse effect. This strategy began with the teacher introducing a problem to elicit students’ prior knowledge and preconceptions. The various complex intertwining processes within greenhouse effect were then untangled and presented in a temporal succession by the teacher, who then linked up the processes in a step-wise fashion. In a separate quasi-experimental study with five German teachers in ten 8th and 9th grade science classrooms, Randler and Bogner (2009) compared an instructional unit on ecology that incorporated inquiry activities, hands-on experiments, field work and cooperative learning strategies, with a traditional teaching unit that involved only worksheets, textbooks and predominantly teacher talk. They concluded that students subjected to the intervention performed better in post- and delayed post-tests on ecological content.
The review on instruction of complex systems uncovered an interesting gap. Despite the numerous novel interventions offering fruitful insights into improving the instruction and learning of complex systems, there has been no study that looks at what and how complex systems ideas are actually taught in regular science instruction. This is disappointing because as explained in the introductory chapter, these ideas are cross-cutting concepts applicable in many science topics and are core in facilitating the understanding of diverse scientific systems. Investigating the instruction of complex systems ideas in typical science classrooms can present a baseline picture of the state of complex systems instruction in school science and identify areas for improvement. Moreover, the existing studies do not consider the relationship between teachers’ understanding and their instructional practices. There is an implicit assumption in the existing studies that teachers already possess an adequate understanding of complex systems. However, as suggested in section 2.2.3, it will be prudent to establish if this relationship is true in the subject matter of complex systems.

To conclude, the review on the teaching of complex systems reveals that existing research has focused on the enactment of innovative interventions to improve student learning of complex systems, phenomena and issues. However, research related to the instruction of complex systems ideas in regular science teaching is oddly non-existent. Questions such as are complex systems ideas taught in regular science classrooms, to what extent are the ideas conveyed, and what relationship exists between teachers’ complex systems understanding and their instructional practices, present an important
angle in appreciating and addressing the educational problem of students’ limited awareness in complex systems.

2.3.4 Reasons for difficulties in understanding and teaching complex systems

The earlier sections have described some difficulties in complex systems understanding. This section looks at what may have given rise to the difficulties in teaching and learning complex systems. Appreciating the factors hindering teachers’ understanding and teaching of complex systems can better direct solutions to address them.

Several reasons have been put forth by researchers and they can be roughly organized into three categories. The first category criticizes the science curricula. As briefly mentioned in the introduction, the way existing science curricula has been typically organized is said to linear and disparate (Mohan, Chen & Anderson, 2009; Sabelli, 2006; Senge et al., 2000). Such curricula fall short of a coherent framework for understanding diverse complex systems. The way science curricula have been set up for teaching and learning about scientific systems, tends to delineate the systems into components for easier understanding and neglect the complexity aspect (Mitchell, 2009; Parnafes, 2010; Resnick, 1994). This approach may work well for teaching and learning about systems that are not complex, but such reductionist approach without a complementary emphasis on the relationships among the components does not facilitate teaching and learning of complex systems (Hmelo-Silver & Azevedo, 2006; Lemke & Sabelli, 2008; Lesh, 2006). The challenge for complex systems instruction then lies in
making sense of the science curricula and emphasizing the complexity in the scientific systems.

The second category of reasons is somewhat related to the first but specifically refers to a lack of instructional resources to engage in complex systems (Klopfer et al., 2009; Jacobson & Wilensky, 2006). Such engagement can mean exploring the ideas of complex systems through curricular and instructional activities, interpreting scientific systems and phenomena from a complex systems perspective and learning about these ideas directly or indirectly through science instruction. In one of their studies, Yoon and Klopfer (2006) noted the difficulties their 47 teacher-participants in a professional development program faced in teaching complex systems using StarLogo, an agent-based modeling tool that allows learners to model and visualize system-level patterns from the perspective of component-level processes. They made several program design changes and found that teachers were more inclined to use the modeling tool if they had ready-made curriculum materials available to them. Pallant, Lee and Pryputniewicz (2012) also argue that having an instructional activity that can be easily implemented in a regular science classroom can encourage the classroom engagement in complex systems, in their case Earth’s climate. Collectively, these studies allude that with more classroom-ready resources for complex systems instruction, the challenges in teaching the ideas may be surmountable.

The third category of reasons argues from a conceptual viewpoint (Resnick & Wilensky, 1998). One hypothesis points to the dominant scientific paradigm that frames people’s cognition. This paradigm which emphasizes reducing systems to the simplest
components and variables, and analyzing them as direct cause-and-effect relationships - much like how one would take apart a clock to see how it works - has been so deeply fixated in people that they generally have trouble in seeing the world in any other ways (Capra, 1996; Yoon, 2008; 2011). Another theory suggests that these conceptual challenges may have arisen because of the different ontological categories the ideas belong to (Chi, 2005; Slotta, 2011; Slotta & Chi, 2006). Defining ontological categories as “the basic categories of realities or the kinds of existence in the world, such as concrete objects, events, and abstractions” (Chi, 2005, p. 163), Chi differentiates between emergent processes which are systemic phenomena occurring as a result of localized interactions at the component level, and direct processes which are also systemic events but arising from direct movements of substances. Slotta (2011) clarifies that many students ontologically perceive emergent processes such as diffusion as direct processes because they have little or no psychological representation of the emergent ontology and hence are unable to ascribe that ontology to these processes. Along similar lines, Wilensky and Resnick (1999) observed students’ and pre-service teachers’ inability to tell apart the behaviors at the component level and the patterns at the system level. They term this phenomenon “confusion of levels” and argue that it is one source of people’s deep misunderstandings about emergent phenomena in the world. “Levels” here refers to descriptions representing the phenomenon at various physical scales (e.g., macroscopic and microscopic). This confusion is believed to be caused by a misguided attribution of intentionality to otherwise random and localized interactions at the component level. Taken collectively, these researchers highlight that the difficulty of understanding
complex systems may have to do with the way people perceive and interpret the processes underpinning these systems.

As plausible as the above-mentioned arguments may seem, these reasons remain hypotheses at best since there has been only one study (Yoon & Klopfer, 2006) to systematically investigate the reasons behind the difficulties in teaching complex systems. However, as that particular study is done in a professional development context of teachers learning to implement a computer modeling intervention, how these reasons hold up in a regular science classroom context requires a separate investigation. It is possible that there may be other teacher-related contextual factors impeding their understanding and instruction of complex systems. An empirical investigation of the reasons behind the challenges will go a long way in deepening the understanding of this issue.

2.3.5 Summary

From this review of teachers’ understanding and teaching of complex systems, four major claims can be made. First, it is fairly conclusive that students have difficulties in construing complex systems to be nonlinear and non-deterministic, possess open and dynamic nature, demonstrate emergent and self-organized patterns, and decentralized. These findings prove the existence of the educational problem described in the introduction. Second, while much is known about student learning of complex systems, the research on teacher understanding is sporadic. The very few studies involving teachers however do suggest that they are likely to face similar difficulties as students. Regrettably, the findings are inconclusive because the studies are small-scale and employ
teacher samples from one or two schools or professional development workshops. Furthermore, the existing studies looked at teachers’ understanding of only a subset of the salient complex systems ideas. Larger and more representative samples and more comprehensive assessments should be undertaken to determine the state of complex systems understanding for a general population of science teachers. Third, there has been no study that examines how complex systems and what complexity ideas are taught or conveyed in regular science classrooms. This is an important aspect to find out because these ideas are cross-cutting concepts applicable in many science topics and are core in facilitating the understanding of diverse scientific systems. Moreover, what teachers teach may be influenced by what they know. Current studies that investigate instructional approaches and strategies to promote student learning of complex systems also do not consider the effect of teacher understanding in this subject matter on their instructional practice. Fourth, the nature of the difficulties in understanding and teaching complex systems is also under-researched. What are teachers’ perceived reasons for their conceptual difficulties and misconceptions? Why are complex systems difficult to teach? Given that there is a prevalence of complex systems misconceptions among students, a thorough investigation of science teachers is crucial in examining the educational problem from the teacher perspective.

2.4 Conceptual framework and research questions

Having established that a study on investigating teachers’ understanding and teaching of complex systems offers potential contributions to the literature, a framework that informs an investigation of the research questions in this study is next articulated.
The framework is conceptualized based on the review of investigating teachers’ understanding and practice, and the gaps identified in the existing literature on complex systems understanding. Figure 1 illustrates pictorially how the conceptual framework is used to guide this study. Encompassing the framework is the subject matter of study – complex systems ideas. There are three main areas of investigation – science teachers’ understanding of these ideas; their instruction of these ideas, and factors that affect their understanding and instruction of complex systems. Findings to these three areas of investigation will help provide a more comprehensive insight into students’ limited awareness of complex systems. It is perhaps necessary to state at this juncture that this research does not test the casual claim that teachers’ understanding and instruction of complex systems affect students’ learning of this field; this will be for a later study.

**Figure 1. Conceptual framework for investigating teachers’ understanding and teaching of complex systems**
Aligned to this framework, the following RQs are formulated. Together, they present a comprehensive approach to finding out the state of science teachers’ understanding and teaching of complex systems.

RQ 1:  a) To what extent do science teachers understand complex systems ideas?

b) Are there complex systems ideas that are more difficult than others for science teachers to understand, and if so, what are they?

RQ 2:  a) To what extent complex systems ideas are conveyed during science teachers’ instructional practices?

b) What is the relationship between science teachers’ understanding of complex systems and their instructional practices?

RQ 3:  What are science teachers’ reasons behind the perceived difficulties in understanding and teaching complex systems ideas?
3 Methodology

3.1 Chapter Overview

How the research is carried out is described in this chapter. To recap, this research examines science teachers’ understanding and teaching of complex systems, specifically, the extent they understand salient complex systems ideas, the extent they convey these ideas during their regular science instruction, the relationship between what they teach and what they know about complex systems, and the reasons that make understanding and teaching complex systems difficult from teachers’ perspective. A mixed methods research design was adopted to cater to the diverse research questions.

Grades 11th and 12th science teachers in Singapore high schools made up the sample in this study. There were two distinct parts in this study. The first part was a large-scale survey of 90 science teachers in six high schools, selected through cluster sampling. These teachers completed two questionnaires – an Understanding of Complex Systems (UoCS) questionnaire and a Perception questionnaire. The UoCS questionnaire contained three peer-reviewed tests, which were designed to assess teachers’ understanding of salient complex systems ideas. The Perception questionnaire aimed to solicit teachers’ views on which complex systems ideas were more difficult than others, what current science topics they incorporated complex systems ideas, and what reasons were behind the challenges in understanding and teaching of complex systems. The second part of the study was an in-depth investigation of teachers’ instructional practice. Six science teachers were purposefully selected and their instructional practices of systems-related topics were video-recorded and transcribed. The six teachers were subsequently
interviewed for their reasons behind the difficulty in understanding and teaching complex systems. Analysis of the survey data and the transcripts of video recordings and interviews helped answer the RQs.

The structure of the rest of this chapter is outlined below:

- **Section 3.2:** A mixed methods research design was adopted to cater to the diverse research questions. Arguments are presented in this section to support the choice of research design.
- **Section 3.3:** Six schools were clustered-sampled from all high schools in Singapore. Reasons for the choice of educational system and number of schools selected, description of how access was sought to the school sites, and information about the selected schools are given in this section.
- **Section 3.4:** Information about participating teachers is described in this section. The scope and sequence of their involvement are also detailed.
- **Section 3.5:** Four data sources – UoCS questionnaire, Perception questionnaire, transcripts of video recordings and interview transcripts were used to gather the data needed to answer the RQs. Detailed information, including how the instruments were developed and how the data were collected, is given.
- **Section 3.6:** Descriptions of how each data source was analyzed is given in this section. There are also discussions on the validity and reliability of the data.
- **Section 3.7:** A logic model is illustrated to conclude this chapter. This logic model presents a reasoned argument as to why the results and conclusions from the study can be considered sound in helping to answer the RQs.
3.2 Mixed Methods Design

A mixed methods research design best suits this study. Creswell and Plano Clark (2007) define this design as one that involves a mixture of qualitative and quantitative approaches in many phases in the research process. In a mixed methods research design, the belief is that the research problem can be better understood and resolved by exploring it from different points of view (Commander & Ward, 2009). It emphasizes the combinatorial use of quantitative and qualitative data for a better interpretation of the phenomenon than either approach alone. Creswell and Plano Clark (2007) explain that this design provides strengths that offset the weaknesses of purely quantitative or purely qualitative methods. The argument rests that on the one hand, quantitative method is strong in its ability to infer and generalize findings to a larger population but weak in understanding the context and allowing the voices of the participants to be heard directly. On the other hand, qualitative research is perceived to be appropriate in providing rich explanatory descriptions to phenomena, but deficient because of the personal interpretations made by the researcher, the ensuing bias created by this, and the difficulty in generalizing findings to a larger group. The use of both methods brings together the strengths of both forms of research to compare and corroborate results for stronger claims.

The research questions and conceptual framework in this study demand a mixed methods research design. RQ 1a, which concerns teachers’ understanding of complex systems, arises because of the limited scope of existing studies; while RQ 1b, which examines the relative difficulty in understanding the various complex systems ideas,
arises because the finding can help inform professional development designers in complex systems what ideas may require more attention. A quantitative survey targeting a representative sample of science teachers is therefore necessary to answer these RQs. RQs 2 and 3, which relate to teachers’ instructional practice of complex systems and the reasons underlying the difficulties they may face, come about because there has yet to be a systemic investigation to these important questions. A quantitative survey with a representative sample can give an overall state of complex systems instruction and an overall picture of the reasons; a more qualitative investigation of the instructional practices with a few teachers can illuminate specifically what complex systems are conveyed while in-depth qualitative interviews with a few teachers may reveal other reasons not listed in the survey.

3.3 Research Context

The study began in January 2013 and the last interview data was conducted in July of the same year. The research was covered under University of Pennsylvania’s IRB (Protocol #816638). Six high schools in Singapore were cluster sampled and all the science teachers teaching Grades 11 and 12 were invited to participate in this study. For most of the participants, they were asked to complete questionnaire surveys. For six purposively selected teachers, their instructional practices were video-recorded and subsequently, these teachers were interviewed concerning the difficulties they faced in understanding and teaching complex systems. In this section, information about Singapore educational system, and the reasons for the choice of this educational system and the school sites, is provided.
3.3.1 Singapore educational system

This study is conducted in Singapore with the teacher sample obtained from high schools – also known as junior colleges – in this educational system. The island state is chosen as a context for three reasons. First, the Singapore educational system offers a relatively stable and homogeneous real-world setting. As it is a small country with a population size of about 5.4 million and an island size of 270 square miles, Singapore’s education system is centrally determined by the Ministry of Education (MOE) in many aspects including the number of schools, students and teachers in each school, school funding, student subsidies, teacher and staff wages, curricula, national examinations, teacher recruitment, student placement, and other educational policies (MOE, 2012; OECD, 2011). In other words, the public schools in this city-state are equitable in terms of school funding, teacher-student ratio, and the physical facilities in the schools. In addition, policy changes generally impact all the schools concurrently. The relative constancy in the environment and the uniformity across Singapore schools compared to other less centralized and more diverse educational systems such as those in the U.S., offers a pseudo-controlled setting, where many systemic variables can be considered similar.

The second reason relates to the quality of Singapore teachers. The OECD report on *Strong Performers and Successful Reformers in Education* (OECD, 2011) describes that Singapore teachers are recruited largely based on their educational qualifications. These teachers generally have academic results that place them among the academic top 30% of their cohorts when they were students. Short-listed teacher candidates then have
to successfully clear interviews helmed by panels of current and former principals, and attend a one-year pre-service preparatory program. In-service teachers are also encouraged to attend regular professional development programs to enhance their professional knowledge and improve their instructional practices. To draw these quality candidates into the demanding profession, attractive compensation and other benefits have been put in place. It has been highlighted in many reports that the exemplary quality of Singapore science teachers may be a contributing factor to the high-performing science and math achievements of her students in international tests (Akiba, LeTendre, & Scribner, 2007; Barber & Mourshed, 2009; Martin et al., 2004; 2008; OECD, 2010; The Economist, 2007). Investigating these highly-qualified science teachers’ understanding of complex systems may help understand those of science teachers in other developed countries.

The third reason is more personal in nature and relates to my own professional relationship with the education system in Singapore. Having worked in a Singapore high school and the Ministry of Education for almost ten years, I am familiar with the operations of Singapore schools and have contacts with many school leaders. The network I have previously established facilitates the administrative and logistical aspects of my research. Furthermore, I have a vested interest in this investigation of Singapore’s teachers because it relates directly to the nature of my work. I hope to make use my findings to influence a change in the science curriculum to emphasize complex systems.

Science teachers teaching 11th and 12th grades – also known as advanced or ‘A’ level – are targeted for this study. At these grades, science comprises of biology,
chemistry and physics, and students have the options to specialize in one to three science subjects. This group of teachers is chosen because their students are more likely to be involved in science-related tertiary studies and professions in the future. In Singapore, not all students move onto 11th and 12th grades. In fact, there are only twenty-five of such schools in Singapore (MOE, 2013). Typically, students in the academic top 30% of each graduating cohort at the 10th grade are offered the opportunity to pursue studies at the ‘A’ levels, and almost all of these students qualify for university education upon graduation (MOE, 2011). With the increasing emphasis of complex systems in modern science, it is prudent to find out if science teachers possess the necessary complex systems understanding for instruction at the ‘A’ level.

3.3.2 Research sites

To investigate science teachers’ complex systems understanding in a systematic manner, six high schools in Singapore were randomly chosen as research sites in September 2012 during this present research proposal defense. As of September 2012, there were almost 650 science teachers in 25 high schools offering ‘A’ level education (MOE, 2013). Sampling of this population frame was required because to assess every one of them would be beyond the means of this dissertation. There are several ways a person can be selected to form part of the actual sample. For this research, a single-stage cluster sampling is appropriate due to its relative ease, and time- and cost-effectiveness of administering the surveys to a large sample (Fowler, 2009). Single-stage cluster sampling refers to clusters or groups of respondents who are first selected by simple random sampling, before all members in the selected clusters are included. The number of
clusters chosen – six in this case – follows the formula provided by Levy and Lemeshow (2008; see Appendix A). In short, six schools were randomly selected from the population of high schools and all science teachers teaching at the ‘A’ levels were included in the sample.

Access to the ‘A’ level science teachers in these six schools was relatively easy but tedious as it required three levels of permission. First, an application was submitted to the MOE for permission to conduct research in Singapore schools. The application was filed in April 2012, and the approval was granted on October 31, 2012 (see Appendix B). By this time, most high schools were already winding down their instructional time in preparation for their year-of-end examinations. This meant that no classroom observations could be done until the start of the next school semester in January 2013. The second level of permission was sought from the school principals. This level of permission was the easiest to obtain. After identifying the six high schools, emails and physical letters were sent to the principals (see Appendix C). Positive replies were received from the six principals and all of them deferred the request to their heads of department in science. The third level of access involved the heads of department of science in each school. Face-to-face meetings with the science heads were arranged to explain about the rationale and scope of the study and the teachers’ involvement. Finally, convenient dates and times for data collection were negotiated.

Table 1 shows a summary of publicly-available demographic information of each school site as of October 2013. The six sites were distributed across the island and located in various types of residential districts – public, private and mixed housing. The
admission criteria to these schools were mainly by academic results in the national examinations. Unfortunately, information regarding the academic performances and socio-economic statuses of the students in each school and relative ranking of the schools could not be obtained because these were confidential data. However, based on unsubstantiated claims from the teachers, these schools represented a wide spectrum of student academic profiles.

Table 1

Demographic information of school sites

<table>
<thead>
<tr>
<th>School</th>
<th>Location in Singapore</th>
<th>Number of teaching staff (rounded off to nearest 10)</th>
<th>Number of science teaching staff</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>North</td>
<td>100</td>
<td>28</td>
</tr>
<tr>
<td>B</td>
<td>Southeast</td>
<td>120</td>
<td>35</td>
</tr>
<tr>
<td>C</td>
<td>West</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>D</td>
<td>Northeast</td>
<td>120</td>
<td>35</td>
</tr>
<tr>
<td>E</td>
<td>Central</td>
<td>130</td>
<td>40</td>
</tr>
<tr>
<td>F</td>
<td>East</td>
<td>70</td>
<td>20</td>
</tr>
</tbody>
</table>

3.4 Participants

There were two levels of research participation in this study. The first level involved the entire sample; teachers’ participation included the completion of two questionnaires (i.e., the Understanding of Complex Systems or UoCS questionnaire and Perception questionnaire). The second level involved six teachers selected from the larger sample; their participation included video recordings of their instructional practices and interviews. In this section, the scope and sequence of the teachers’ involvement for each level are first described before describing the profiles of these teachers and explaining how they were selected.
3.4.1 Survey Participants

Teachers’ participation in the first level of the study entailed the completion of two survey questionnaires (i.e., UoCS and Perception questionnaires). The questionnaires were administered to the teachers in the sampled schools during data collection sessions. The teachers first completed the UoCS questionnaire which sought to assess their understanding of complex systems. This took 45 minutes. The Perception questionnaire was administered after the UoCS questionnaire. The Perception questionnaire aimed to solicit teachers’ views about teaching and understanding complex systems, in particular what ideas are more difficult than others, what current science topics do teachers already incorporate complex systems ideas, and what reasons are behind the challenges in understanding of complex systems. This took 10 minutes. In all, the administration of the two surveys required about an hour of the participants’ time.

All science teachers in the selected schools were invited to participate in this study. The number of 11th and 12th grades science teachers in these schools varied between 20 and 40. Only 94 out of a total of 183 possible teachers (excluding those on longer-term leave) turned up during the data collection sessions. The research involvement and confidentiality clause were explained to the teachers at the start before they were asked to sign the consent forms (see Appendix D). Of these 94 teachers who turned up, 90 consented to participate. This translated to a moderate response rate of 49% of the entire intended sample. Table 2 shows the breakdown.
Table 2

Breakdown of participating science teachers in various schools

<table>
<thead>
<tr>
<th></th>
<th>School</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of science teachers teaching Grades 11 and 12</td>
<td></td>
<td>28</td>
<td>35</td>
<td>25</td>
<td>35</td>
<td>40</td>
<td>20</td>
<td>183</td>
</tr>
<tr>
<td>Number of science teachers participate in professional development sessions</td>
<td></td>
<td>18</td>
<td>13</td>
<td>13</td>
<td>23</td>
<td>17</td>
<td>10</td>
<td>94</td>
</tr>
<tr>
<td>Number of science teachers who give consent</td>
<td></td>
<td>17</td>
<td>13</td>
<td>13</td>
<td>20</td>
<td>17</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>% of science teachers in school who give consent</td>
<td></td>
<td>61%</td>
<td>37%</td>
<td>52%</td>
<td>57%</td>
<td>43%</td>
<td>50%</td>
<td>49%</td>
</tr>
</tbody>
</table>

Fowler (2009) stated that it is important to understand the reasons for nonresponse as it may introduce bias to the findings. 89 teachers did not turn up during the data collection sessions. A check with their heads of department largely showed that the non-participating teachers were on sick leave, were undergoing professional development or were having lessons with their students. There was little cause to suspect nonresponse bias as their absence appeared coincidental. Although there were 18 of them who simply did not turn up, this constituted 10% of the sampling frame which should not skew the findings too significantly.

Forty-one percent of the 90 consenting teachers were beginning teachers with less than three years of teaching experience, and 30% had taught for more than ten years. Refer to Figure 2 for the distribution of their years of teaching experience. This proportion was largely reflective of the general teacher population (MOE, 2013). There was also relatively good representation of male (54%) and female (46%) teachers. The various subjects were well-represented too, with 24% Biology teachers, 39% Chemistry teachers, and 37% Physics teachers. This compares relatively well with the general
population of 15%, 45% and 40% for 11th and 12th grades Biology, Chemistry and Physics teachers respectively. Refer to Figure 3 for an illustration of the teachers by gender and teaching subjects. All participating teachers were all teaching within their subject specializations, that is, they were teaching subjects related to their undergraduate science or engineering degrees.

Figure 2. Number of participating teachers and their years of teaching

Figure 3. Number of participating teachers by gender and teaching subjects
3.4.2 Classroom video recording and interview participants

The second level of the study involved an in-depth investigation of six teachers’ understanding and instructional practice. The teachers’ participation included video recordings of their instructional practices and interviews. Six was deemed as the optimal number of teachers I could realistically investigate in six months as the video recordings required considerable time – about five hours for each teacher – to be spent in the classrooms. A balance was struck between ensuring a somewhat equitable representation of teachers from the three science subjects and making do with a limited amount of resources available to me.

Selection of these six teachers was based on two criteria: i) each subject – biology, chemistry, and physics – was represented by two teachers; and ii) these teachers were perceived by their supervisors to be able to articulate the challenges of teaching science. In other words, purposive sampling was used to represent diversity in subjects and increase the likelihood of getting rich narrative data (Cohen et al., 2007). The first criterion took into account the three science subjects offered at the ‘A’ level. There would likely be systematic differences in the way complex systems ideas are translated into the instruction of biology, chemistry and physics. The second criterion considered teachers’ insights into the challenges of teaching science and their capacity to reflect and talk about the complexity of science teaching (Meister, 2010; Lieberman & Mace, 2009). Based on their supervisors’ recommendations, these teachers were more likely able to provide rich narratives during the interviews.
There were three broad steps in this selection process. First, enquiries were made with the science heads of department in the six schools regarding their science teachers. Specifically, they were asked “among your science teachers, who should I approach if I am interested to find out more about how science is taught and learned in the classrooms,” “why do you recommend this teacher,” “would you say this teacher is able to tell me about the challenges in teaching science?” Typically, the departmental heads would recommend two or three teachers to me. Second, after the teachers were identified, a meet-up session was scheduled with each identified science teacher to explain the aim of the research and the purpose of the observations. During the session, the recommended teachers were also asked some questions such as their years of teaching experience, what makes them enter the teaching profession, and what their greatest satisfaction is in teaching science. Through their responses to these basic questions, the ability of the teachers in articulating their views was determined. It was acknowledged that this informal assessment was based purely on my subjective judgment, but it sufficed as a rough gauge of their ability to articulate. Third, the process was repeated with a different teacher until the required teachers across the three science subjects were recruited. In all, twelve teachers were approached between November 2012 and January 2013, and six agreed to participate in the study. Information about the six teachers, together with the topics they taught, is given next. Pseudonyms are used.

Elly, biology teacher. Elly was a biology teacher who taught Grade 12 students. She had a bachelor in life sciences from the National University of Singapore. She had taught for three years and headed the biology unit in her school. According to Elly, her
students were academically above-average in her school. Elly understood complex systems as she learned about emergence and self-organization in some of her biology undergraduate courses. Elly was teaching Diversity and Evolution during the video recordings. Briefly, this topic covers the concepts of species, variation, natural selection and evolution. It also covers the neo-Darwinian revolution and the evidence of evolution. Among the learning outcomes, students are required to show an understanding of the biological, ecological, morphological and phylogenetic concepts of species, and explain speciation with reference to geographical, physiological and behavioral isolation. They are expected to explain natural selection, particularly how natural selection may bring about evolution, the importance of variation in this process, and how anatomical, embryological and molecular homology provide evidence for Darwin’s theory of natural selection. They are also required to describe the neutral theory of molecular evolution.

Jeremy, biology teacher. Jeremy was a biology teacher who taught Grade 11 students. He had a bachelor in biology from the National University of Singapore. He had taught for six years. According to Jeremy, his students were academically average in his school. Although Jeremy claimed to know little about complex systems, he has attended a module on systems thinking during his graduate studies but he was unsure if these were related. Jeremy was teaching Cellular Functions, and DNA and Genomics during the video recordings. Briefly, the topic of Cellular Functions covers the detailed structure of typical animal and plant cells, functions of organelles in plant and animal cells, structures of carbohydrates, lipids and proteins and their roles in living organisms, and the process of cell replication. Among the learning outcomes, students are expected to interpret
photographs of typical cells as seen under the electron microscope, recognizing various
membrane systems and organelles and outlining their functions. They are also required to
describe the formation and breakage of glycosidic and peptide bonds, analyze the
molecular structure of a triglyceride and phospholipid, and relate their functions to their
structures. The topic of DNA and Genomics covers the structure and function of DNA.
Students are expected to describe the structure and roles of DNA and RNA, including
tRNA, rRNA and mRNA, and describe the process of DNA replication and the
experimental evidence for semi-conservative replication.

*Bill, chemistry teacher.* Bill was a chemistry teacher who taught Grade 12 students.
He also had a bachelor in chemistry from the National University of Singapore and a
master of science in instructional technologies from the Nanyang Technological
University. Bill had five years of teaching experience. He recently assumed a subject
headship position in information communications technology in his school. Bill described
his students as “bright” and “should do very well in the exam.” Bill had heard about
complex systems but was unsure what it is really about. He was teaching Organic
Chemistry during the video recordings. Briefly, this topic requires the students to
compare and contrast the different mechanisms of organic reactions. When describing
preparative reactions, they are expected to quote the reagents, the essential practical
conditions, and the products. They are also required to suggest what steps may be needed
to purify and extract a required product from the reaction mixture. Several kinds of
organic compounds, including alkanes, alkenes, halogen derivatives, hydroxyl
compounds, carbonyl compounds, and carboxylic acids, are listed as topics for learning in the syllabus.

*Willie, chemistry teacher.* Willie was a chemistry teacher who taught Grades 9 to 11 students. He had a bachelor in chemistry from the National University of Singapore. Willie had four years of teaching experience. According to Willie, the students he taught typically score above-average results. He also mentioned that he had some prior knowledge of complex systems as he attended a module in the use of agent-based modeling software during his undergraduate study. He was teaching the topic of Kinetic Particle Theory during the video recordings. Briefly, the Kinetic Particle Theory describes a model for behaviors at the particulate level. Students are required to learn that particles vibrate about average fixed positions when held in place by forces of attraction or bonds, and move at higher speeds when energy is supplied to overcome these forces or bonds. At a systemic level, the particles appear to be moving in random and constant motion. They are also required to understand about diffusion, which describes the net movement of particles from a region of higher concentration to one of lower concentration.

*Casey, physics teacher.* Casey was a physics teacher who taught Grade 12 students. She had a joint bachelor in physics from the National University of Singapore and the École Centrale Paris in France, and a master of science in engineering from both universities. Casey had three years of teaching experience. According to Casey, she taught students of mixed academic abilities. Casey was aware of complex systems from her undergraduate course, but she claimed she could “not remember much.” She was
teaching Electricity and Electromagnetism during the video recordings. Briefly, the topic of Electricity covers the concepts of current, voltage, and resistance. Students are required to learn and solve problems using the various equations for current, charge, electromotive force, potential difference, resistance, and power. They are also expected to apply these equations and concepts to explain and solve circuit problems involving various components such as thermistors, light-dependent resistors and potential dividers. The topic of Electromagnetism covers the concepts of magnetic field strength and the effects due to the interactions of the field and current or moving charges. Students are required to show an appreciation that a force might act on a current-carrying conductor placed in a magnetic field, and be able to solve problems using Lorentz force equation.

Johnny, physics teacher. Johnny was a physics teacher who taught Grade 11 students. He had a bachelor in civil and structural engineering and a master of science in science education from the Nanyang Technological University. Johnny worked as a civil engineer for three years before joining the teaching service. He had taught for nine years and headed the science department in the school. According to Johnny, his students “did not particularly face difficulties in understanding physics.” In terms of his prior knowledge in complex systems, he had read up on it after being introduced to the field during our initial conversations. He was teaching the topic of Work, Energy and Power during the video recordings. Briefly, this topic covers the concepts of work, energy conversion and conservation, different energies, and power. Students are required to show an understanding of the concept of work and to calculate the work done in a number of situations. They are also expected to give examples of energy in different
forms, its conversion and conservation, and apply the principle of energy conservation to solve problems. They also need to derive the formulae of power, kinetic and potential energies, and apply these formulae in different situations.

3.5 Data Sources

The data sources, which included questionnaire surveys of a representative sample of science teachers, and video recordings and interviews of six purposively-targeted teachers, are discussed in this section. Why were these data sources chosen?

As explained in section 3.2, these qualitative and quantitative data complemented each other’s strengths and made up for each other’s weaknesses in this study’s mixed methods research design. Surveys as data sources are useful in facilitating broad and representative insights of teachers’ complex systems understanding. The two surveys allowed systematic estimates of teachers’ understanding and perceptions in a rigorous fashion (Czaja & Blair, 2005; Fowler, 2009). This was crucial in providing generalizable descriptions of teachers’ state of complex systems understanding and perceptions. While the surveys were useful to gain a broad overview of teachers’ complex systems understanding, the video recordings of lessons and interviews of a small number of teachers can capture and provide a nuanced description of their understanding and teaching of complex systems in context (Cohen, Manion & Morrison, 2007).

Table 3 shows a map of the data sources in relation to the RQs: (i) a UoCS questionnaire survey to assess teachers’ complex systems understanding; (ii) a Perception questionnaire survey to seek teachers’ responses on how they perceive the challenges in understanding complex systems ideas and how they believe they have translated these
ideas into their instructional practices; (iii) video recordings of six teachers’ lessons to capture their classroom instruction of systems-related topics; and (iv) interviews of the same teachers to probe the reasons for any difficulty they faced in understanding and teaching complex systems. Each data source is discussed in turn.

Table 3

Data sources map

<table>
<thead>
<tr>
<th>Research Questions</th>
<th>Surveys: ( N_1 = 90 )</th>
<th>Video recordings and interviews: ( N_2 = 6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UoCS questionnaire</td>
<td>Video recordings</td>
</tr>
<tr>
<td>RQ 1a</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>RQ 1b</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>RQ 2a</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>RQ 2b</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>RQ 3</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

3.5.1 Understanding of Complex Systems (UoCS) questionnaire

A UoCS questionnaire which incorporated three tests of complex systems understanding was administered in a survey to the sample of 90 science teachers across six data collection sessions in schools. To recap, RQs 1 seek to find out the extent science teachers understand complex systems ideas and the relative difficulty in understanding these ideas. The findings were crucial in making sense of students’ limited complex systems awareness because of a likely relationship between student learning and teacher understanding. The findings could also inform future professional development in complex systems. In the following sections, the considerations underpinning the choice of assessments (section 3.5.1.1), the assessments themselves (section 3.5.1.2), and the data collection process (section 3.5.1.3) are described.
3.5.1.1 Choice of assessments

There are several peer-reviewed assessments on complex systems understanding in the literature (e.g., Booth-Sweeney & Sterman, 2007; Jacobson, 2001; Jacobson et al., 2011; Penner, 2000; Plate, 2010; Yoon, 2008), it was prudent to explore how they could be adapted and incorporated in this questionnaire, rather than developed a new one altogether. The choice of assessments was guided by four particular considerations, namely: contexts of the assessment questions; the types of assessments; the coverage of salient complex systems ideas; and the overall length of the questionnaire.

Contexts of assessment questions. An individual’s knowledge is dynamically coupled with the context in which the knowledge is situated (Brown, Collins & Duguid, 1989; Clancey, 1997; Plate, 2010; Sadler, 2009). Roth (1998) advocates that assessing one’s knowledge should consider a variety of question contexts as the contexts can affect how one thinks. Calling this “ecological validity” (p. 165), he explains that the same concepts assessed in a variety of contexts (e.g., ecosystem, bodily system, physical systems) can better gauge what the respondents actually know. Indeed, question contexts have been argued to be an important factor in designing tests for complex systems understanding because there are suggestions that one’s thinking of complex systems may be affected by his or her available domain-specific knowledge of particular complex systems (Ekborg, 2005; Gotwals & Songer, 2010; Levy & Wilensky, 2008; Metz, 1998; Penner, 2000; Plate, 2010). To enhance the ecological validity of the results, questions involving different complex systems can help mitigate influences of teachers’ domain-specific knowledge.
Types of assessments. The manner teachers are asked about the subject matter also affects their performances on the tests because various types of assessments (e.g., written responses, concept maps, and multimedia) solicit different information about what they know (Mislevy et al., 2000). Roth (1998) cautions about the inherent situated nature of assessment practices and that reliance on a single test often leads to a “situation where we know little about the properties of purportedly underlying phenomena, only what they look like through the imposition of test format” (p. 165). Tucker (2009) advocates multiple forms of representations – written, visual, and graphical – to assess respondents’ understanding. Investigations of teachers’ complex systems understanding should include a variety of assessment formats so as to account for the situated nature of their understanding.

Coverage of ideas. The assessments should collectively cover key complex systems ideas. This is crucial since one of the reasons for having RQs 1 is to address the gap in the literature that existing studies have only looked at teachers’ understanding of a subset of the salient complex systems ideas. More comprehensive assessments should be undertaken to determine the state of complex systems understanding for a general population of science teachers.

Overall length. The first three considerations were related to the nature of the assessments; the fourth concerned the overall length of the questionnaire. Respondent fatigue presents a threat to validity of the results; there was a real possibility of the survey participants becoming less attentive and accurate in their responses should the questionnaire took a long time to complete (Brace, 2008; Cohen et al., 2007; Fowler,
Keeping the survey session as short as possible without compromising on the information needed was a balancing act. It was arbitrarily decided that the entire questionnaire could be completed within 45 minutes, about a regular class period. Pilot of the questionnaire with three teacher-friends prior to the study proved that this timeframe was feasible; subsequent actual tests also did not surface any noticeable respondent fatigue.

Based on these considerations, three tests of complex systems understanding developed by Goh, Yoon and their colleagues (2012), Jacobson and his research team (2011), and Plate (2010) were adapted for the questionnaire. The assessments from Jacobson and his team (2011) tested the understanding of emergence, self-organization and decentralization using natural phenomena of birds and ants; the exercise from Plate (2010) assessed the understanding of nonlinearity and non-determinism, and open and dynamic nature using a socio-scientific issue; and the open-ended ecology question from Goh, Yoon and team (2012) examined the understanding of all key ideas using a park ecosystem. The former two assessments were quantitative in nature, while the latter was qualitative. They collectively required 35 minutes to complete.

3.5.1.2 Description of UoCS questionnaire

In all, there were four parts to the questionnaire (refer to Appendix E). Part A contained demographic questions, while Parts B to D comprised of the three assessments. To recap, RQs 1 seek to find out the extent science teachers understand complex systems ideas and the relative difficulty in understanding these ideas. Table 4 provides a
summarized description of the various parts and what ideas each assessment measured. Each part is next described in turn.

Table 4

*Description of parts in UoCS questionnaire*

<table>
<thead>
<tr>
<th>Part of Questionnaire</th>
<th>Part A</th>
<th>Part B</th>
<th>Part C</th>
<th>Part D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Assessment</td>
<td>Demographic questions</td>
<td>Visualization exercise</td>
<td>Causal mapping exercise</td>
<td>Open-ended question</td>
</tr>
<tr>
<td>Context</td>
<td>-</td>
<td>Natural phenomena</td>
<td>Socio-scientific issue</td>
<td>Ecosystem</td>
</tr>
<tr>
<td>Estimated length of time</td>
<td>5 minutes</td>
<td>10 minutes</td>
<td>15 minutes</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Complex systems ideas</td>
<td>Non-determinism and nonlinearity</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open and dynamic nature</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emergence and self-organization</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decentralization</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

*Part A: Demographics.* There were seven questions in Part A which gathered demographic information about the teacher-participants. These included the school they taught in, the number of years in teaching, the science subjects they taught, their education majors, and their prior knowledge on complex systems. The data was used to describe the general characteristics of the sample as well as determine if there are significant differences in their understanding of complex systems amongst the various groups of teachers.

*Part B: Visualization exercise.* Part B consisted of two questions based on visualizations of natural phenomena. These questions were adapted from the *Complex Systems Knowledge Mediator* (CSKM: Jacobson et al., 2011). Jacobson and his
colleagues developed this hypermedia program to instruct learners on some key concepts of complex systems. They built into the program several questions to assess learners’ understanding of complex systems ideas of emergence, self-organization and decentralization.

The first question required teachers to view two computer visualizations which animated how ants find food. One of it showed a decentralized model of ants’ foraging behavior. Ants leave their colony and wander around randomly. Upon finding a food source, they return to the nest with bits of the collected food. As they return, they deposit a chemical trail that decreases in intensity with time. Other ants on picking up this trail move toward the food source. The other visualization showed a centralized model whereby a leader ant first goes out from the colony to find food. When she finds a source, she picks up some and deposits a chemical trail as she returns to the nest. The rest of the ants then follow the trail to get more food. Figures 4 and 5 show screenshots of the decentralized and centralized models respectively.
Figure 4. Screenshot of a decentralized model

Figure 5. Screenshot of a centralized model
After viewing these two visualizations, the teachers selected the model they thought best represents ant foraging behavior. They also gave a reason for their choice. Figure 6 shows the question and choices the teachers were given.

1. Models of ants

Place a tick in the box next to the model you think best represents ant foraging behavior.

<table>
<thead>
<tr>
<th>Model</th>
<th>Best describes what I believe about ant foraging behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video 1: Worker ants leave their colony and wander around randomly to find food. Upon finding a food source, they return to the nest with bits of the collected food, and deposit a chemical trail that decreases in intensity with time. Other ants on picking up this trail move toward the food source.</td>
<td></td>
</tr>
<tr>
<td>Video 2: A leader ant first goes out from the colony to find food. When she finds a source, she picks up some and deposit a chemical trail when she returns to the nest. The worker ants then follow the trail to get more food until there is no more food.</td>
<td></td>
</tr>
</tbody>
</table>

Explain your choice briefly.

---

**Figure 6. Question on ants’ foraging behavior**

The second question asked teachers for their thoughts on how birds form and stay together in flocks. This question aimed to assess their understanding of emergence and self-organization. A video clip on starling flocking in seemingly organized formation (see Figure 7 for a screenshot of this clip) was shown to the teachers before they were asked to choose statements that they believed to be true. Table 5 shows the list of belief statements. Half of the statements described beliefs that the formation of flocks is intentional and that the patterns are dictated by certain leader birds. For instance, birds form flocks to protect themselves by being in a group, and there are certain ‘leader’ birds
that the others follow to form flocks. The other half communicated the perceptions that the formation is unintentional but an emergent and self-organized consequence of localized bird flying behaviors. The teachers were to pick at least two statements that best described their beliefs.

*Figure 7. Screenshot of starling flocking video clip*

**Table 5**

*Belief statements about how birds form and stay together in flocks.*

<table>
<thead>
<tr>
<th>Non-emergent and intentional belief statements</th>
<th>Emergent and self-organized belief statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) There are certain ‘leader’ birds that the others follow to form flocks.</td>
<td>(b) Birds align themselves as they fly by steering towards the average heading of their local flockmates.</td>
</tr>
<tr>
<td>(c) Birds form flocks to protect themselves by being in a group.</td>
<td>(e) A flock is held together because the birds will steer to move toward the average position of local flockmates.</td>
</tr>
<tr>
<td>(d) Leader birds communicate with the other birds to tell them which way to go using special sounds.</td>
<td>(f) As birds fly, they steer so that they are not too close to each other.</td>
</tr>
<tr>
<td>(h) Birds form flocks because they need to migrate.</td>
<td>(g) There are no leader birds; any bird may be at the head of the flock at any given time.</td>
</tr>
<tr>
<td>(j) Birds form flocks because they get scared by other animals near the group and fly away.</td>
<td>(i) Birds try to stay with other birds that are like themselves.</td>
</tr>
</tbody>
</table>

*Note.* The letters in parentheses indicate the order the statements were presented in the questionnaire.
**Part C: Causal mapping exercise.** This part comprised of a causal mapping exercise adapted from Plate (2006; 2010). Teachers’ understanding of nonlinearity, and open and dynamic nature of complex systems was ascertained from this exercise. The teachers first read an article of a fictitious fishing controversy involving a made-up “samaki” fish. This controversy mirrored a real-world socio-scientific issue of the U.S. menhaden fishery - menhaden refers any forage fish of the genera *Brevoortia* and *Ethmidium*. This article provided various perspectives on the declining population of samaki and the impact of samaki on the marine ecosystem, agriculture, and economy (see Appendix G for the samaki article). Teachers were asked to put away the article after reading and they were guided to develop their causal maps.

As the name implies, a causal map is a physical representation of their perceptions of the causal relationships between items on the map. In his study involving middle school students, Plate used a causal mapping technique to evaluate their understanding of causal structures in complex systems. Causal structures are frameworks that people develop mentally in order to represent the dynamics of complex systems. These causal structures can range from perceiving systems as having simple linear relationships (e.g., an increase in A leads to an increase in B, which in turn causes C to increase) to seeing them as involving in web-like nonlinear interactions (e.g., an increase A leads to increases in B and C, but B also causes C to decrease, and an increase in C may cause a feedback to A). Plate explained that in this mapping technique, it is typical to ask participants to show linkages among the key system components or concepts (called nodes), and indicate the effects of these linkages on their maps. By examining the density
of linkages to nodes and the number of causal loops in these constructed causal maps, the level of their understanding of nonlinearity and dynamic nature of the system can be measured.

The teachers looked through a list of ten concepts (see Table 6) – each expressing an aspect of the issue – and circled those concepts they felt necessary in order to explain the issue to a peer who is unfamiliar with it. The teachers were then asked to start with any two from their selected concepts and perceive the relationship between them given three possibilities: (i) increase in Concept A directly increases Concept B or decrease in A directly decreases B (+); (ii) increase in A directly decreases B or decrease in A directly increases B (-); or (iii) no relationship. The teachers indicated their perceived relationship by drawing arrows from cause A to effect B. An arrow with a positive sign (+) from A to B indicates choice (i). An arrow with a negative sign (-) indicates choice (ii). If there is no perceived relationship, they did not have to draw a link.

Table 6

*Concepts used in fishery article*

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Algae blooms in coastal sea</td>
<td>D</td>
<td>Demand for animal feed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G</td>
<td>Production from fish-oil competitors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J</td>
<td>Samaki population</td>
</tr>
<tr>
<td>B</td>
<td>Amount of samaki caught</td>
<td>E</td>
<td>Predatory marine animal and bird population</td>
</tr>
<tr>
<td>C</td>
<td>Demand for omega-3 food supplement</td>
<td>F</td>
<td>Price of competing products (e.g., soybeans, vegetable oils)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I</td>
<td>Samaki industry profits</td>
</tr>
</tbody>
</table>


A simple example was given in the questionnaire on how to illustrate the relationships among the concepts. Three concepts were given: “number of cars on the road,” “car sales” and “car prices” (see Figure 8). When there is an increase in the number of cars sold (i.e., “car sales” concept), the number of cars on the road should increase. So an arrow is drawn from the concept “car sales” to the concept “number of cars on the road” with a positive sign to indicate a direct relationship. “Car prices” should have an inverse relationship on “car sales” – an increase in car prices is perceived to decrease the number of cars sold as they are more expensive. Therefore another arrow is drawn “car prices” to “car sales” with a negative sign to indicate the inverse relationship.

One other possible relationship can be perceived in this example – “car sales” can have a direct effect on “car prices.” When the number of cars sold decreases, dealers may reduce the prices of the cars to boost sales. Another arrow can be drawn from “car sales” to “car prices” with a positive sign to indicate the nature of this relationship.

**Figure 8.** Example of causal map given in questionnaire

After going through the example, the teachers were asked to evaluate the causal relationships among all potential concept pairs they chose in a similar manner and draw
them in the space provided on the questionnaire. They were reminded to consider causality in both directions with each pair. That is, does the effect B also affect the cause A? The final product was a drawn map displaying the causal connections. Figure 9 shows one such drawn map.

Figure 9. A teacher’s causal map

Plate argues that this method can illuminate participants’ level of systems thinking. He reasons that those untrained in such thinking are less likely to look for nonlinear
causal links and feedback loops. For instance, in Figure 9, even though there is a bidirectional relationship between J (samaki population) and E (predatory marine animal and bird population), that is, an increase in the samaki population can increase the population of the predatory marine animals and birds but an increase in the predatory populations can decrease the number of samaki, the teacher did not perceive it. He merely indicated with an arrow from J to E without the causal link from E back to J in a feedback loop. The question, in other words, seeks to find out whether the teachers could identify the relationships on their own, giving a more accurate depiction of their state of complex systems understanding in the socio-scientific issue presented.

Part D: Open-ended question. This part contained an open-ended ecology question from a previous study by Goh, Yoon and their colleagues (2012). The teachers provided qualitative answers to this question, which was modified slightly for a Singapore context.

A park ecosystem consists of both living (biotic) and non-living (abiotic) elements. These elements (e.g., animals, plants, water, soil, rocks) interact with one another in various ways. Now, imagine a flock of geese arriving in MacRitchie Reservoir where geese have not lived before. Describe how the addition of these geese affects the ecosystem over time.

This question was developed by the research team from the DRK-12 BioGraph project (Yoon, Klopfer, et al., 2013; Yoon, Koehler, et al., 2014). This project, funded by the National Science Foundation, works with teachers and students to develop complex systems understanding in the content area of biology through computational simulations (specifically StarLogo TNG), pedagogical resources and professional development. As part of this project’s assessment of students’ understanding of complex systems ideas, a series of biology questions have been designed and vetted. This particular question concerning the effects of geese migration was deemed as capable of soliciting
respondents’ understanding of the various complex systems ideas after extensive piloting with some 44 students in the early stages of the project (Goh et al., 2012). Furthermore, because this question allowed the expression of all four salient ideas, analysis of the relative difficulty of the complex systems ideas (RQ 1b) was possible.

3.5.1.3 Data collection

The UoCS questionnaire was administered during data collection sessions in the six schools between January and May 2013. A common script to administer the questionnaire was developed and read for all sessions (see Appendix F). The teachers completed this questionnaire in my presence. A researcher-facilitated survey has an added advantage in reducing item-nonresponse, that is, the situation where there is incomplete or no response to the questions asked in a questionnaire (Czaja & Blair, 2005). Item-nonresponse can be problematic because it may be linked to certain characteristics of the sample. If certain groups of respondents tend not to answer particular questions, this may skew the findings. By guiding the teachers through the instrument in person, it encourages them to answer all the items in it. Indeed, the nonresponses were from teachers who either turned up late for the session (six teachers) or left early for other school duties (one teacher). In all, there were 87 fully completed questionnaires.

3.5.2 Perception questionnaire

A Perception questionnaire was administered shortly after the UoCS questionnaire to the sample of 90 teachers during the same data collection sessions. The various ideas of complex systems were explained to the teachers just prior to the administration of the
Perception questionnaire; the descriptions of these ideas given were similar the ones in section 2.3.1.

The Perception questionnaire was designed to capture data about the relative difficulty in understanding the various complex systems ideas (RQ 1b), the extent these ideas were translated in practice (RQ 2a), and the reasons for the difficulties in understanding these ideas (RQ 3). The various parts in this questionnaire (section 3.5.2.1) and the data collection process (section 3.5.2.2) are described in the following sections.

3.5.2.1 Description of Perception questionnaire

There were three parts to the Perception questionnaire. Refer to Appendix H for the questionnaire.

*Part A: Ranking of categories of complex systems ideas.* Teachers were asked to rank the four categories of complex systems ideas in order of their difficulty in understanding. Insight into the teachers’ perceived relative difficulty in understanding the various ideas can inform the future professional development efforts to enhance science teachers’ knowledge of complex systems. Teachers were given four empty boxes beside each category of ideas (i.e., nonlinearity and non-determinism; open and dynamic nature; emergence and self-organization; and decentralization) to indicate their relative ranks. Figure 10 shows one of the teachers’ responses.
Part A

1. Of these four categories of complex systems ideas you have learned, rank them (1 = least difficult ... 4 = most difficult) in order of your difficulty in understanding.

<table>
<thead>
<tr>
<th>Category</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinearity and non-determinism</td>
<td>3</td>
</tr>
<tr>
<td>Emergence and self-organization</td>
<td>1</td>
</tr>
<tr>
<td>Open and dynamic nature</td>
<td>2</td>
</tr>
<tr>
<td>Decentralization</td>
<td>4</td>
</tr>
</tbody>
</table>

*Figure 10. A teacher’s response to Part A of Perception questionnaire*

Part B: Reflection on teaching. Teachers were asked to state whether they have incorporated complex systems ideas in their lessons in the past six months. Affirmative responses can give an indication of the proportion of science teachers who have done so and this can provide an overview of the extent to which these complex systems were translated into practice. The teachers were also asked about the topics in which complex systems ideas were incorporated and how. *Figure 11* shows a teacher’s response.

*Figure 11. A teacher’s response to Part B of Perception questionnaire*

One salient problem with recall questions, such as this one in Part B, is the respondents’ ability to remember the events in question accurately (Cohen et al., 2007). Saris and Gallhofer write that the longer the reference period is, the “more unlikely it is that one can reproduce the requested information from memory” (2007, p. 85). Some
researchers suggest providing a realistic time frame of the past events that respondents are supposed to remember and allowing them sufficient time to recall during data collection (e.g., Cohen et al., 2007; Fowler, 2009). With these recommendations in mind, Part B asked the teachers to recall their teaching in the past six months and ample time was given for them to complete the questionnaire.

**Part C: Reasons for difficulties in understanding complex systems.** Teachers were asked if complex systems ideas are difficult to understand, and why. Finding out the reasons for the learning difficulties teachers may face can help surface key issues to address so as to facilitate the classroom instruction of these ideas. Teachers chose, from a list of possible reasons, statements that explained their perceived difficulties. This list of possible reasons was developed after a review of the literature on reasons underlying conceptual difficulties in complex systems refer to section 2.3.4). These reasons could be roughly grouped into curriculum (e.g., the curriculum does not emphasize these ideas), learning (e.g., I need additional information and learning experiences to understand them), beliefs (e.g., I do not think these ideas are scientifically valid), and ontology (e.g., it requires a fundamental shift in my current understanding of scientific phenomena). To cater to other reasons that were not listed, teachers were also free to add other reasons. Figure 12 shows a teacher’s response to Part C.
### Figure 12. A teacher’s response to Part C of Perception questionnaire

#### 3.5.2.2 Administration of questionnaire

The Perception questionnaire was administered shortly after the teachers completed the UoCS questionnaire. In-between, they had a short break and a 30-minute explanatory session on the various ideas of complex systems after the UoCS questionnaire. They were then given the Perception questionnaire to complete. The questionnaire was self-explanatory and required minimal instruction from me. The teachers took about 10 minutes to complete. A collection box was placed by the exit for teachers to return their completed questionnaires before they left. In all, there were 85

<table>
<thead>
<tr>
<th>Reason</th>
<th>Yes / No (please circle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The current science curriculum does not emphasize these ideas.</td>
<td></td>
</tr>
<tr>
<td>I do not believe that these ideas are scientifically valid.</td>
<td></td>
</tr>
<tr>
<td>I need to learn about these ideas by experiencing with models depicting complex systems.</td>
<td></td>
</tr>
<tr>
<td>I feel that these ideas are not generally accepted in the scientific community.</td>
<td></td>
</tr>
<tr>
<td>These ideas somewhat contradict ideas and concepts in the current science curriculum.</td>
<td></td>
</tr>
<tr>
<td>I have trouble perceiving most scientific phenomena with these ideas.</td>
<td></td>
</tr>
<tr>
<td>I require more learning opportunities that convey these ideas.</td>
<td></td>
</tr>
<tr>
<td>These ideas do not fit into the topics in the science curriculum.</td>
<td></td>
</tr>
<tr>
<td>I need additional information about these ideas.</td>
<td></td>
</tr>
<tr>
<td>I believe that such cross-disciplinary ideas cannot exist.</td>
<td></td>
</tr>
<tr>
<td>Understanding the ideas require a fundamental shift in how I view scientific phenomena.</td>
<td></td>
</tr>
<tr>
<td>It will take time to change my perception of complex systems.</td>
<td></td>
</tr>
</tbody>
</table>

Other reasons (please explain):
fully completed questionnaire received as 5 participants left the sessions early due to school-related duties.

3.5.3 Video recordings

Video recordings of the six teachers’ lessons gathered information on their instructional practices. These recordings were subsequently transcribed verbatim. The information from the transcripts was used to answer what complex systems ideas were conveyed during science teachers’ instructional practices, how explicit were the ideas taught and what the relationship exists between science teachers’ understanding of complex systems and their instructional practices? Recall that a review of the literature reveals that very little is known about complex systems instruction in regular science lessons, investigating science teachers’ teaching of systems-related topics and relating their instruction to their understanding of complex systems can provide insights into the educational problem of students’ limited awareness in complex systems from the teacher perspective. In the following sections, video recordings as a viable data source (section 3.5.3.1), data collection process (section 3.5.3.2) and transcription process (section 3.5.3.3) are discussed.

3.5.3.1 Video recordings as a data source

While surveys are useful instruments to gain a broad overview of teachers’ complex systems understanding, video recordings of teachers’ lessons can capture rich and contextual descriptions of their practices (Cohen, Manion, & Morrison, 2007; Jewitt, 2012; Roth, 2007; Roth et al., 2011). As RQs 2 ask how teachers convey complex
systems, descriptions of their practices upon which analyses can be based will be useful (Mitchell, 2011; Smith & Jang, 2011).

The use of video as an investigative tool in social science, including education, has been well-documented. The National Centre for Research Methods at the Institute of Education, London (Jewitt, 2012) and the Data Research and Development Center at the University of Chicago (Derry, 2007) consolidate developments in this method and lay out guidelines in the scope and use of video in research. Among the various uses of video for research, video-based fieldwork – or the collection of naturally occurring data using video cameras – is the most common and established use of video for data collection. The key advantage of video is that it can provide a fine-grained multimodal record of an event detailing both the verbal and non-verbal acts in which all action and talk are kept in context and recorded sequentially. The recordings enable researchers to “rigorously and systematically examine resources and practices through which participants in interaction build their social activities and how their talk, facial expressions, gaze, gesture and body elaborate one another” (Jewitt, 2012, p. 6).

However, researchers also caution about the collection of massive amounts of data, which can lead to overly descriptive analysis. The scope of investigation needs to be carefully managed so as not to overwhelm the subsequent analysis or neglect important aspects of the social phenomenon (Derry, 2007; Jewitt, 2012). Snell (2011) offers that researchers collecting information on video can adopt a systematic way to observe, sort, store, organize, code and analyze the rich data. These can include having pre-established coding schemes for observing the video, and transcribing the video recordings and
treating the transcripts as artefacts for subsequent analysis (Bezemer & Mavers, 2011). For instance, Smith and Jang (2011) were able to search for affordances and constraints to their teacher’s science teaching using transcripts of the video recordings of her lessons. Likewise, Mitchell (2011) reported how she could distill differences in implementation between an augmented reality and a paper-based control version of a mathematics curriculum unit from transcripts of recordings. In this present study, the video recordings were trained on the six teachers. The recordings were then transcribed with emphasis on the instructional speech and actions. The data collection process is detailed next.

3.5.3.2 Video recording process

As described in section 3.4.2, the lessons to be recorded were negotiated with the six teachers. This was to ensure that the teachers were comfortable in being recorded. One topic was agreed for each teacher and all the lessons for that chosen topic were recorded. These chosen topics were cellular functions and evolution in biology; organic chemistry and particulate nature of matter in chemistry; and work, energy and power, and electricity and electromagnetism in physics; the topics were all related to complex systems. The video recordings took place between January and July 2013. Each lesson period lasted about 50 minutes. For each teacher, there were six to seven periods in all. This amounted to 30 hours of recordings in all.

To ensure that the teachers and students were not overly affected by my presence, two additional sit-ins and mock recordings were scheduled prior to the actual recordings. This was also to familiarize me with the routines of the classes. A video camera was set up on a tripod at the back of the room, focusing on the teacher. A standby audio recorder
was also placed on the teacher’s desk but this data source proved unnecessary as the audio and video captured by the video camera were clear. Information about the classroom environment which otherwise would not be captured on video were noted. This classroom information included the number of students, gender distribution, seating arrangement, and time and date of the recordings. At the end of each lesson, the video recording was transferred to a personal laptop.

3.5.3.2 Transcription process

The video recordings were transcribed typically within a week of recording. The format of the transcripts followed the recommendation in the Guidelines for Video Research in Education document (Derry, 2007). An example of a transcript can be found in section 2.6.3.2. The transcripts provided verbatim descriptions of what the teacher said and supplemented by what the students responded. Non-verbal actions and other contextual information, such as what the teacher did or showed, were written in parentheses. Recordings showing actions and speech that were not particularly related to the teaching and learning of the topics were only cursorily mentioned. Such instances include the teacher managing behavioral issues in the class or performing administrative duties. Other contextual information, in particular the number of students, gender proportion, time and date of recording, for each lesson was also dutifully written into the opening paragraph of each transcript of the recordings. The transcripts provided detailed illustrations of what went on during the lessons. They became the artefacts on which analysis was performed.
3.5.4 Interviews

Semi-structured interviews with the six teachers aimed to find out the reasons behind difficulties in understanding and teaching about complex systems. As there has been no research to systematically investigate why teachers may find complex systems difficult to understand and teach, examining the reasons from teachers’ perspective can inform future reform efforts in complex systems instruction. In the following sections, the rationale for using semi-structured interviews (section 3.5.4.1) and the data collection process (section 3.5.4.2) are discussed.

3.5.4.1 Use of semi-structured interviews

Semi-structured interview as a data collection method reflects an ontological position that is concerned with “people’s knowledge, understandings, interpretations, experiences and interactions” of a phenomenon (Mason, 2004, p. 1020). Smith and Osborn (2003) suggest that the focus is getting the individual’s personal perception of the phenomenon, as opposed to an attempt in producing an objective statement of the phenomenon itself. In this method, the interviewer retains some control over the direction and content to be discussed, but participants are free to elaborate or take the interview in new but related directions (Barriball & While, 1994; Bernard, 1988; Marshall & Rossman, 2006; Wengraf, 2001). In other words, this is a research method where the interviewer is free to follow new leads as they arise.

A semi-structured interview was necessary to gather data for RQ 3 because of the different lesson scenarios played out in the various teachers’ classrooms. It was necessary to adapt the line of questioning to the scenarios and guide the teachers in explicating the
reasons why challenges in understanding and teaching complex systems might occur. Semi-structured interviews have been used in other studies examining understanding of complex systems or exploring instructional challenges. Levy and Wilensky (2008) in their study of students’ reasoning of the formation of familiar complex phenomena used a semi-structured interview method. They explained that a semi-structured method was necessary to gradually guide the students in elaborating their perceptions of how various scenarios involving complex social patterns are formed. Park and Oliver (2009) also employed a semi-structured interview approach to explore the challenges influencing instructional strategies used by teachers in gifted science classrooms. Nielsen (2012) too engaged such a method to distill the difficulties and reasons for the difficulties for implementing an innovation from a professional development project. Generally, these authors argue that this method offers the interviewee the opportunity to add further information and elaborate on their responses.

3.5.4.2 Data collection process

All interviews with the teachers were about an hour long and they were audio-taped. They were conducted in an enclosed and quiet room in their respective schools. These interviews were conducted typically within a fortnight after the final recordings; two teachers were however interviewed about a month later because they were away during the June vacation.

An interview began with a reiteration of the research’s aims and some simple questions about the teacher’s teaching experience to put the teacher at ease (Cohen et al., 2007). These questions included “how long have you been teaching,” “is this your first
school,” and “what did you like about teaching?” This ‘ease-in’ segment took about five minutes.

The ‘ease-in’ segment was followed by a ten-minute explanation of complex systems and the ideas. A seven-minute long video titled *Introduction to Complex Systems* (Schoenfeld, 2013) was also shown to Bill, Casey, Johnny and Willie. This video was added because from the first two interviews (i.e., Elly and Jeremy), it was reviewed that the explanation could be enhanced with a short instructional video. The video, featuring Dr. Eric Klopfer of Massachusetts Institute of Technology, was found suitable as a short introduction to the subject matter.

Next, the teacher was asked to watch some segments of his or her lessons captured on video. This was necessary to help the teachers recall what they taught so as to ground their responses and prompt discussion. In other words, the ‘play-back’ segments served as video elicitation (Jewitt, 2012). The segments, such as instruction on the random movement of particles in a system and nonlinear retarding forces, were picked for the complex systems ideas that were conveyed during the lessons.

A semi-structured interview protocol (see Appendix I) guided the interviews. This protocol was designed with different lesson scenarios in mind. For instance, a teacher was seen to teach a concept from a complex systems perspective. He was first guided to clarify how he explained the concept seen in the video segment. He was then asked if he was aware of the complex systems ideas this concept can be related to. Suppose he was unaware, he was then told how his instructions of, say, diffusion reflected a decentralized notion. He was next asked what difficulties he might face in understanding and teaching
this complex systems idea in the context of the topic he was teaching and subsequently
the reasons for the difficulties. Conversely, suppose he was aware of his decentralized
perspective of diffusion, he would be directly asked for the difficulties and reasons for
these difficulties in understanding and teaching this idea. Other scenarios (not discussed
here but see Appendix I) led to various lines of questioning.

3.5.5 Summary

To summarize, it has been argued in section 3.2 that a mixed methods methodology
is most appropriate for investigating the RQs which demand both qualitative and
quantitative approaches. The large-scale survey questionnaires afforded an overall and
representative description of the state of teachers’ complex systems understanding and
instruction, while the small number of targeted classroom recordings and teacher
interviews offered the contextual specifics into their practices and reasons in the
difficulties to learn and understand complex systems ideas. The combinatorial use of the
various quantitative and qualitative instruments supported a comprehensive, valid, and
well-substantiated investigation of the RQs.

3.6 Data Analyses

In the previous section, the data sources and collection methods were described. As
this study was a mixed methods design, there were quantitative and qualitative data
components to analyze. Primarily, SPSS version 21 quantitative analysis software and
ATLAS.ti 7.1.3 qualitative analysis software were used to aid in the analyses. The
following sections are organized according to the RQs. Each section has a similar
3.6.1 RQ 1a: To what extent do science teachers understand complex systems ideas?

To make sense of the educational problem of students’ limited awareness of complex systems, it has been earlier argued in section 2.2.2 that it is necessary to investigate teachers’ own complex systems understanding. RQ 1a was answered from the analyses of the three tests of complex systems understanding in the UoCS questionnaire with further breakdown of the analyses by the demographic information of the teachers.

Recall that there were four parts within the UoCS questionnaire. Part A captured demographic information, Part B looked at the teachers’ understanding of emergence and self-organization, and decentralization through their interpretations of natural phenomena, Part C solicited their understanding of nonlinearity and non-determinism, and open and dynamic nature through their causal maps depicting a complex socio-scientific system, and Part D examined their understanding of the four sets of salient complex systems ideas through their qualitative responses to an ecology question about the effects of geese on a park system. In other words, the teachers’ understanding of the key complex systems idea was assessed using one of the tests in Parts B or C, and the ecology question in Part D. How the data was analyzed is next described.

3.6.1.1 Visualization exercise

The visualization exercise in Part B of the UoCS questionnaire assessed the teachers’ understanding of emergence and self-organization, and decentralization.
Emergence and self-organization. A video clip on the natural flocking behaviors of birds was shown to the teachers. At the end of their viewing, a list of ten belief statements was given and they were asked to choose at least two statements that best fit their beliefs on how birds form and stay together in flocks (see section 3.5.1.2). As half of the ten statements were related to emergent and self-organized behaviors, whereas the other half communicated intentional behaviors, the relative proportion of the statements chosen illustrated their prevailing beliefs. Table 7 gives an interpretation of the proportion.

Table 7

<table>
<thead>
<tr>
<th>Proportion</th>
<th>Interpretation of emergent and self-organized belief statements chosen</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.33</td>
<td>Non-emergent and intentional belief</td>
</tr>
<tr>
<td>0.33 – 0.66</td>
<td>Somewhat emergent and self-organized belief</td>
</tr>
<tr>
<td>&gt; 0.66</td>
<td>Emergent and self-organized belief</td>
</tr>
</tbody>
</table>

To demonstrate how the relative proportion was calculated, a teacher’s response is used as an example (see Figure 13). The response was accorded a score of 50% as four ‘emergent and self-organized’ statements (circled) and four ‘intentional’ statements were selected, Based on this score, this response was categorized as having a somewhat emergent and self-organized belief of the phenomenon. The prevailing mindset among the teachers can be determined statistically.
2. Birds flocking

Select the statements you believe describes the phenomenon you have just seen in the video. “I believe birds form and stay together in flocks because…” (tick at least two statements)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>There are certain ‘leader’ birds that the others follow to form flocks.</td>
</tr>
<tr>
<td>b.</td>
<td>Birds align themselves as they fly by steering towards the average heading of their local flockmates.</td>
</tr>
<tr>
<td>c.</td>
<td>Birds form flocks to protect themselves by being in a group.</td>
</tr>
<tr>
<td>d.</td>
<td>Leader birds communicate with the other birds to tell them which way to go using special sounds.</td>
</tr>
<tr>
<td>e.</td>
<td>A flock is held together because the birds will steer to move toward the average position of local flockmates.</td>
</tr>
<tr>
<td>f.</td>
<td>As birds fly, they steer so that they are not too close to each other.</td>
</tr>
<tr>
<td>g.</td>
<td>There are no leader birds; any bird may be at the head of the flock at any given time.</td>
</tr>
<tr>
<td>h.</td>
<td>Birds form flocks because they need to migrate.</td>
</tr>
<tr>
<td>i.</td>
<td>Birds try to stay with other birds that are like themselves.</td>
</tr>
<tr>
<td>j.</td>
<td>Birds form flocks because they get scared by other animals near the group and fly away.</td>
</tr>
</tbody>
</table>

Figure 13. A teacher’s response to bird flocking behaviors with emergent statements circled

Decentralization. The teachers also viewed two simulations of ants foraging behaviors. These two simulations attempted to find out whether the teachers have decentralized or centralized perceptions of complex phenomena. As they had to choose one of the two models of foraging behavior, a simple frequency count of the teachers who selected each model was undertaken. This allowed a straightforward description of the dominant mindset possessed by these participants. In addition, the teachers were asked to provide rationales for their choices. This gave a qualitative portrayal of their perceptions. Figure 14 illustrates a teacher’s response.
3.6.1.2 Causal mapping exercise

The causal mapping exercise in Part C of the UoCS questionnaire assessed the teachers’ understanding of nonlinearity and non-determinism, and open and dynamic nature.

Nonlinearity and non-determinism. The teachers were asked to produce causal maps of a socio-scientific issue by connecting concepts with arrows that illustrated their perceptions of causal relationships. The teachers’ causal maps were scored quantitatively for their Web-like Causality Index, which provided the proxy measurement for their understanding of nonlinearity and non-determinism. This index was also used in Plate’s (2006; 2010) study as an analytical technique to assess respondents’ complex systems understanding.

The Web-like Causality Index measures the node-link density in each map. A concept (or node) may have more than one link connecting it to other concepts, and the
concept can be either a cause or an effect. Causes are concepts perceived to affect a particular concept, whereas effects are other concepts perceived to be affected by the particular concept. Based on previous works by Eden, Ackerman, and Cooper (1992), Jenkins and Johnson (1997), and Kearney and Kaplan (1997), Plate illustrates that one can measure the degree to which an individual includes web-like causality on their maps by calculating for each map the proportion of concepts with more than one cause and the proportion of concepts with more than one effect. These two values are summed to produce the Web-like Causality Index. In a completely linear and deterministic map, no concept will have more than one cause and one effect; the Web-like Causality Index score is zero. A score of 1 roughly means that half of the listed concepts have more than one effect, and half have more than one cause, implying that the participant has a nonlinear and non-deterministic perception of the scenario. In other words, the larger the Web-like Causality Index score, the more a teacher has stepped away from having purely linear causal structures. Table 8 gives an interpretation of the scores.

Table 8

*Interpretation of Web-like Causality Index scores*

<table>
<thead>
<tr>
<th>Score</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.33</td>
<td>Linear and deterministic</td>
</tr>
<tr>
<td>0.33 – 0.66</td>
<td>Somewhat nonlinear and non-deterministic</td>
</tr>
<tr>
<td>&gt; 0.66</td>
<td>Nonlinear and non-deterministic</td>
</tr>
</tbody>
</table>

To illustrate how the Web-like Causality Index score can be calculated, two causal maps produced by teachers are used as examples. The causal map in Figure 15 contained nine concepts. Only Concept J has more than one effect, as indicated by the four arrows leaving it to four other concepts. No concept has more than one cause. Therefore, in this
map, the Web-like Causality Index score is $\left(\frac{0}{9}\right) + \left(\frac{1}{9}\right) = \frac{1}{9} = 0.11$. It is categorized as a linear and deterministic map.

![Causal map example with a Web-like Causality Index score of 0.11](image)

*Figure 15. Causal map example with a Web-like Causality Index score of 0.11*

The causal map in Figure 16 contained six concepts. Concepts G and H have more than one effect, as indicated by the two arrows leaving them. Concepts B and J have more than one cause, as indicated by the two arrows pointing to them. Therefore, in this map, the Web-like Causality Index score is $\left(\frac{2}{6}\right) + \left(\frac{2}{6}\right) = \frac{2}{3} = 0.67$. It is categorized as a nonlinear and non-deterministic map.
Figure 16. Causal map example with a Web-like Causality Index score of 0.67

Open and dynamic nature. The second measure in this exercise was the number of causal loops in the maps. Plate and other researchers (Moxnes, 2000; Perkins & Grotzer, 2005; Raia, 2005) argue that reinforcing and balancing feedback loops play major roles in the workings of complex systems. To understand fully the dynamic nature of these systems, one needs to have an implicit awareness that there is no apparent beginning, middle, or end point in such loops (Booth-Sweeney & Sterman, 2007; Jacobson, 2001). In other words, one should be aware that the processes inherent in these loops are non-static and always evolving with time. For example, the fish population decreases when amount of fish caught increases, but this decrease in the former may cause less fish to be caught. The initial cause (number of fish caught) becomes the effect over an extended timeframe. Plate (2010) opines that the number of such loops in a map should correspond to an individual’s level of understanding of the dynamic nature of complex systems. That is, a low number of causal feedback loops illustrates a lack of understanding of these ideas. A map with no loop portrays an isolated and static view; a map with one or two loops depicts a somewhat open and dynamic perception; and a map with more than two
loops demonstrates that the teacher has an open and dynamic perception of the fishery socio-scientific issue. Table 9 summarizes an interpretation of the scores.

Table 9

*Interpretation of number of loops in causal maps*

<table>
<thead>
<tr>
<th>Number of Loops</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>Isolated and static perception of system</td>
</tr>
<tr>
<td>1 – 2</td>
<td>Somewhat open and dynamic perception of system</td>
</tr>
<tr>
<td>&gt; 2</td>
<td>Open and dynamic perception of system</td>
</tr>
</tbody>
</table>

To illustrate how the number of loops was counted, one of the teachers’ causal maps was used as an example. In Figure 17, there were two loops: I \(\rightarrow\) B \(\rightarrow\) J \(\rightarrow\) I; and G \(\rightarrow\) B \(\rightarrow\) J \(\rightarrow\) I \(\rightarrow\) G), indicating a somewhat open and dynamic perception of the system. The causal maps in Figures 15 and 16 on the other hand, did not feature any feedback loop.

*Figure 17. Causal map example with two feedback loops*
3.6.1.3 Open-ended ecology question

Recall that the ecology question of the UoCS questionnaire asked teachers to explain, as fully as they could, the effects of geese on a park ecosystem. Their qualitative explanations were coded and analyzed for their understanding of the various complex systems ideas using a Complex Systems Ideas Categorization Manual (CSICM; Appendix J). This manual was developed based on previous studies by Yoon (2008) and Goh, Yoon, and colleagues (2012), which in turn were adapted from Jacobson’s (2001; Jacobson et al., 2011) original work. This section describes how the CSICM captures the nuanced understanding of the various complex systems ideas implicit in the written responses.

To clarify, the intent of the CSICM was not to assess the conceptual accuracy of the ecology content; rather it described variations in teachers’ understanding of complex systems ideas. In the CSICM, complexity understanding was delineated into the four categories of complex systems ideas. In order to account for variations in their understanding of complex systems within each category of ideas, each response was coded for three levels of increasing sophistication: Clockwork (Level 1), Somewhat Complex (Level 2), and Complex (Level 3). Clockwork responses encompassed those that showed linear, deterministic, enclosed, static, centralized, and intentional system interactions and states, whereas complex responses included those that demonstrated non-linear, non-deterministic, open, dynamic, decentralized, emergent, and self-organized system interactions and states.
Nonlinearity and non-determinism. Under the category of Nonlinearity and Non-determinism in CSICM, a response had a score of 1 (clockwork) if it implied that the way the geese affected the other components in the park was completely predictable, and that the interactions among the components were linear with no feedback structure. For example,

when the geese are there, I think that it would greatly affect the people who go there. A lot of people would leave because of the bird poop.

The definitive tone and the singular, unidirectional effect of the geese suggested a linear and deterministic perception. A response had a score of 3 (complex) if it suggested unpredictability in the outcomes following geese’s arrival, and presence of feedback mechanisms in the park ecosystem. For instance,

Since the geese arrive at a place they haven’t ever been before, there are many ways they can affect the ecosystem and it is impossible to say exactly how. For example, they could drive other birds away so that they can lay eggs. They could drive other birds away because they compete for the same kind of food. They could cause the increase of other animals who feed on geese because the geese have become an alternative food source for existing predators. The geese decrease in numbers. It’s really hard to tell.

The uncertain tone and presence of multiple connections with feedback between the geese and different parts of the system suggested a non-deterministic and nonlinear perception. A score of 2 was given when either non-deterministic or nonlinear implications were present in the answer.

Open and dynamic nature. Under the category of Open and Dynamic Nature in CSICM, a response to the ecology question scored a level 1 if it implied that the changes to the park were completely static (i.e., the change process terminates once a certain outcome is reached), and that the park was completely bounded (i.e., other components that are not immediately connected to the park need not be considered). For example,
When geese arrive in the park, it would greatly affect the people who go there. A lot of people would leave because of the amount of bird poop. People would also leave because of all the birds flying around. The statues in the park would be corroded and fall off, which also cause people to leave...

This response perceived a static change – the behaviors of the geese would drive people away. It also saw the park as an isolated system; it did not consider other elements, such as climate, humans and presence of other places. A response would get a score of 3 if it suggested that the changes were part of an on-going process where the system was in a constant state of flux, and demonstrated that the other ‘less noticeable’ components within or outside of the system were considered. For example,

*The geese would eat some animals to survive. This increases the competition for the same food with other animals. The other animals may leave the park to seek greener pastures. They and the geese may also simply starve, and their populations decrease. However, over time, with more geese in the park, the amount of nutrients in the soil is likely to increase as there are more decaying matter (feces and dead geese). This allows the park to support more animals. At the same time, overcrowding may occur. The lack of space may again decrease the populations.*

The dynamic nature was apparent in this response. Suggestions that populations of animals undergo cyclic variations implied that the respondent was aware of the non-static nature of the changes. At the same time, nutrients – a not-so-visible component of the park system – were mentioned as an important and contributing component to the system, and this hinted at an understanding of the open nature of complex systems. A score of 2 was awarded when implications of either open or dynamic nature were present in the answer.

*Emergence and self-organization.* Under the category of *Emergence and Self-organization* in *CSICM*, a response to the ecology question would get a score of 1 if it implied a non-emergent and intentional nature in the formation of the systemic patterns.
In other words, there was a sense that the geese’s actions caused localized changes only, and that these patterns were pre-determined with specific purpose in mind. For instance,

_The geese are staying because they probably have a good resource of food here. They want to eat the bugs and decrease their numbers._

The decrease in bug population was considered a localized change because it was seen as a direct effect of the geese’s arrival. The response also indicated intentionality for the geese’s arrival, that is, they ‘want’ to stay because of the presence of food. A response had a score of 3 if it suggested a possibility of small action leading to large effects (i.e., emergence) and that the systemic patterns were not pre-determined. For example,

_The geese will probably help the ecosystem. First, their droppings might make the soil more fertile, and plants will grow better. There may be more O2 as a result. The result of O2 and plant increase could cause a wet and warm ecosystem._

There was a clear indication of emergence in this response. The geese’s arrival could result in a change in the climatic conditions of the park. There was no indication that the geese had intended for this to happen, and that the ‘wet and warm ecosystem’ was a pattern that self-organized as a result of the interactions of various components. A score of 2 was given when implications of either non-intentionality or emergence were present in the answer.

*Decentralization.* Under the category of *Decentralization* in CSICM, a response would get a score of 1 if it implied that the geese is the central agent of the park and all the changes were determined by the geese alone. For instance,

_The geese arrival would drive other birds away... less worms as geese eats them._

This response perceived the geese as the main actor of the park. No other components that might influence or affect the changes caused by the geese were implied. A response
had a score of 3 if it suggested the presence of more than two central agents that might influence changes.

*When geese come to the park, they will eat most of the grass. There will be a decrease in the food that geese eat. The caterpillars and the other grass-eaters will starve, die or move to another place. This means the decomposers will have less to eat, and probably decompose any dead geese faster. The soil may have less nutrients and the trees may grow less green.*

In this exemplar, the geese, the grass, the decomposers, and the soil (i.e., four agents) were reasoned to play a part in influencing other parts of the system. This suggested an understanding of the idea of decentralization. A score of 2 was given when only two central agents were implicated in the answer.

To help make sense of the various analyses for the data collected from different tests, Table 10 summarizes these analyses which are used to answer RQ 1a.

Table 10

*Summary of analyses for RQ 1a*

<table>
<thead>
<tr>
<th>Tests of complex systems</th>
<th>Complex systems ideas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nonlinearity and non-determinism</td>
</tr>
<tr>
<td>Part B: Visualizations</td>
<td>-</td>
</tr>
<tr>
<td>Part C: Causal mapping exercise</td>
<td>Web-like Causality Index</td>
</tr>
<tr>
<td>Part D: Ecology question</td>
<td>Scores in CSICM</td>
</tr>
</tbody>
</table>

**3.6.1.4 Demographic information**

Apart from the three complex systems tests, the UoCS questionnaire also contained seven demographic questions in Part A. This demographic data was analyzed in four
ways. First, the information was used to provide simple description about the sample. This description could then be compared with the known variables in the entire population of 11\textsuperscript{th} and 12\textsuperscript{th} grades science teachers in Singapore to give a sense of the sample’s representativeness. The information has already been described in section 3.4.1.

Second, as the schools were cluster-sampled, it was necessary to see if there were significant differences between schools and within schools as this may result in bias in the results (Kaplan & Keller, 2011; Kerry & Bland, 1998). The school information captured was used to test for homogeneity in the teachers’ complex systems understanding within schools. First, the scores of the various tests were standardized and summed to produce a total complexity score for each participant. Next, a one-way ANOVA was used to examine whether the participants’ total complexity score is a function of the schools they were teaching in. The independent variable represented the six schools and the dependent variable was the total complexity scores. The Shapiro-Wilks test for normality and homogeneity of variance were also performed to determine if the assumption underlying the application of ANOVA was met.

Third, one of the questions asked the teachers if they are “aware of complex systems, complexity, complex science, or complexity science.” 16 or 18\% of the 90 science teachers surveyed responded ‘yes’. In other words, 16 of the teachers surveyed had prior knowledge of complex systems. From the short descriptions given, these teachers have heard about this field either in their general reading of science or during their undergraduate and postgraduate studies. The total complexity scores of these 16 teachers were compared with those of the remaining teachers without prior awareness
using one-way ANOVA (or an independent t-test could also be used in this case of two independent groups). The independent variable represented their prior awareness and the dependent variable was the total complexity scores. This provided greater clarity on whether this group of teachers had a significantly different extent of complex systems understanding from those teachers who have yet to receive instructions on this topic.

Fourth, the teaching subject information was used to determine if their understanding of complex systems varied with their teaching subjects. The total complexity scores of these teachers were compared across teachers teaching biology, chemistry and physics. In other words, the independent variable represented their teaching subject and the dependent variable was the total complexity scores. This analysis could yield useful information about the differential perceptions of complex systems among the teachers.

3.6.1.5 Validity and reliability discussion

Validity and reliability of the individual complex systems tests in the UoCS questionnaire is discussed in this section.

Visualization and causal mapping exercises. The visualization and the causal mapping exercises in Parts B and C of the UoCS questionnaire were direct adaptations of the original studies by Jacobson and his team (2011) and Plate (2006) respectively. Content validity and face validity of these two exercises were checked. Content validity typically requires the use of recognized subject matter experts to evaluate whether the assessment items in the exercises accurately define the content of assessment, which in this case, complex systems understanding (Trochim, 2006). University professors
knowledgeable in the field of complex systems have validated the exercises for both Jacobson’s (2001; 2011) and Plate’s (2006) studies. A pilot of the two exercises was performed with four science teachers, who were not part of the survey sample, for face validity (Robson, 2002). All pilot teachers gave feedback that the instructions were easy to understand and they were able to explain the intent of the exercises clearly.

A test-retest reliability check was not done for the two exercises. Typically for test-retest reliability, they involve the participants doing the exercises twice with some time lapse between the tests. However, in this case, there was a likelihood that the pilot teachers would ‘learn’ from the initial testing (Feder, 2008; Trochim, 2006), producing results which would lean toward greater complexity understanding in the re-tests.

Ecology question and CSICM. Determining the validity and reliability was more complicated for Part C of the questionnaire. Validity of the ecology question was ascertained in the previous study from where the question was derived (Goh, Yoon et al., 2012). As for the validity of the CSICM – the instrument to code the responses of this question, previous versions of this manual were constructed and validated with student responses, therefore this CSICM needed to be re-validated with teacher responses.

First, the validity of CSICM was done with a doctoral student who was involved with the development of a previous version of the instrument (Goh et al., 2012). Specifically, her role was to vet through the CSICM’s descriptions and variations across the levels of complexity. Slight alterations were made to enhance the CSICM’s clarity across the categories of complex systems ideas and the levels of complexity. Second, to ensure that the coding manual was reliable in scoring the qualitative responses, Cohen’s
kappa inter-rater reliability (IRR) test was performed on SPSS version 21 using three independent raters on a randomly-selected 20% of the 90 qualitative responses. There are four stages to this IRR process, namely: (i) selection of raters; (ii) training of raters; (iii) scoring of responses; and (iv) results of IRR test.

(i) Selection of raters: There were three independent raters (including me). I was one of the raters in this IRR test because I was the sole rater for the rest of the qualitative responses; it was necessary to ensure that the scores I assigned were aligned to the manual and to the interpretation of other raters. The other two raters, Raters A and B, were advanced doctoral students in the fourth or fifth years (at the time of scoring) of their doctoral studies at the University of Pennsylvania and Harvard University respectively. These two raters were purposely selected because they had prior experience in coding qualitative responses using prepared manuals. Rater A is a former high school Biology teacher, was knowledgeable in the subject matter of complex systems as she was involved in DRK12 BioGraph, the research project mentioned earlier to enhance high school students’ biology understanding through complex systems ideas. She helped to develop an earlier version of this categorization manual (Goh et al., 2012) and was the person who vetted and provided advice on this current version. Rater B was a former high school Mathematics and Physics teacher. He was not as well-versed in complex systems as Rater A, so significantly more time was invested to train Rater B. However, his strong
scientific background allowed him to grasp an understanding of complex systems ideas fairly quickly, and this facilitated the training process.

(ii)  

*Training of raters:* The training of the two raters was done separately, within two weeks of each other in April 2013. For each category in the *CSICM*, about fifteen minutes were used to train Rater A and forty-five minutes for Rater B. All training sessions began in similar fashion. First, the raters were guided through the theoretical construct of a particular category of complex systems ideas. The ideas were explained to them and examples of how these ideas could be seen in familiar complex systems (e.g., traffic jams and birds flocking phenomena) were given. Next, the raters were led through the scoring definitions for the category. Each level (i.e., Complex, Somewhat Complex, and Clockwork) was read aloud together and exemplars representing each level were explained. The raters were then asked if they had any questions. Following their verbal agreement that the scoring descriptions were clear to them, they were progressively given four sample responses to score. These responses were obtained from the pre-pilot of the UoCS questionnaire with four science teachers. A think-aloud strategy was used to better understand the raters’ decision-making processes (Lasky, 2012; Lochhead, 2001). After scoring each sample response, they were asked to talk about the rationale for giving the particular score. I then stated my score and explained why I agreed or disagreed with them. Finally, the rater’s difficulties in interpretation of the qualitative responses were deliberated and the areas
for improvement were noted. Although no changes were made to the scoring
descriptions, additional exemplars were added for clarity.

(iii) *Scoring of responses:* 18 responses were randomly selected from the data set.
The scoring of these responses by the two raters was performed immediately
after the training of each category in the *CSICM*. Both raters spent between
20 and 40 minutes to score the 18 responses for each category of complex
systems ideas. They rated the responses independently in my presence. In
other words, there were no interruptions from me during their scoring. In all,
the training and scoring were performed over two sessions for Rater A and
four sessions for Rater B. I also rated these 18 responses at the same time
with Rater A. After the scores were assigned, they were keyed into a
spreadsheet for subsequent IRR analysis.

(iv) *Results of IRR test:* An inter-rater reliability (IRR) test suggested by Light
(1971) for a fully-crossed design (i.e., a subset of the respondents rated by a
same set of coders) with more than two raters was used to analyze the scores.
This IRR test, modified from the original Cohen’s kappa statistic which was
intended for two raters, involved computing kappa statistic for all coder pairs
then using the arithmetic mean of these estimates to provide an overall index
of agreement. The mean kappa statistic obtained was between 0.78 and 0.85
for the four categories, and 0.82 overall, which could be qualified as
“substantial” to “almost perfect agreement” (Landis & Koch, 1977). Table 11
shows the breakdown of this IRR analysis for each category of complex
systems ideas and for the overall CSICM. In sum, the CSICM was found to be a reliable instrument for analyzing the responses to the ecology question.

Subsequently, I coded the rest of the responses.

Table 11

Average kappa statistic for IRR test on the use of CSICM

<table>
<thead>
<tr>
<th>Category</th>
<th>Symmetric Measures</th>
<th>Raters</th>
<th>Value</th>
<th>Asymp. Std. Error</th>
<th>Approx. T</th>
<th>Approx. Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Nonlinearity and nondeterminism)</td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.800</td>
<td>.133</td>
<td>4.003</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A and me</td>
<td>.793</td>
<td>.140</td>
<td>3.885</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.800</td>
<td>.133</td>
<td>4.003</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Average Kappa</td>
<td>A, B, and me</td>
<td>.798</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B (Open and dynamic nature)</td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.829</td>
<td>.115</td>
<td>4.921</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A and me</td>
<td>.829</td>
<td>.115</td>
<td>4.921</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.829</td>
<td>.115</td>
<td>4.921</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Average Kappa</td>
<td>A, B, and me</td>
<td>.829</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (Emergence and self-organization)</td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.778</td>
<td>.140</td>
<td>3.656</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A and me</td>
<td>.891</td>
<td>.101</td>
<td>4.124</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.880</td>
<td>.116</td>
<td>3.761</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Average Kappa</td>
<td>A, B, and me</td>
<td>.850</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D (Decentralization)</td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.780</td>
<td>.143</td>
<td>3.394</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A and me</td>
<td>.780</td>
<td>.143</td>
<td>3.394</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.775</td>
<td>.150</td>
<td>3.288</td>
<td>.001</td>
</tr>
<tr>
<td></td>
<td>Average Kappa</td>
<td>A, B, and me</td>
<td>.778</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All categories</td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.806</td>
<td>.066</td>
<td>8.410</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A and me</td>
<td>.829</td>
<td>.062</td>
<td>8.676</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.827</td>
<td>.063</td>
<td>8.537</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Average Kappa</td>
<td>A, B, and me</td>
<td>.821</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Mean kappa statistic for three raters (Light, 1971)

3.6.2 RQ 1b: Are there complex systems ideas that are more difficult than others for these teachers to understand, and if so, what are these?

A broad goal of the study is to plan appropriate professional development content in understanding and teaching complex systems. Understanding the relative difficulty in
interpreting the various complex systems ideas can potentially guide the design of such professional development. RQ 1b was answered from the analyses of the responses to the open-ended ecology question in Part D of the UoCS questionnaire and Part A of the Perception questionnaire. The analysis of the relative difficulty of the salient ideas is next described. This is followed by a discussion on the validity and reliability of the data analyses.

3.6.2.1 Open-ended ecology question

In the original study from which this question was derived, Goh, Yoon, and their colleagues (2012) explained how the Generalized Partial Credit Model (GPCM: Muraki, 1992) was applied to analyze the relative difficulties in articulating the various ideas. GPCM is an item response theory model. The items, or categories of salient complex systems ideas in this case, were conceptualized as a series of hierarchical levels of performances where a teacher received partial credit for successfully performing at a particular level. Since the coding included three levels of understanding for four categories of complex systems ideas (see section 3.6.1.3), analyzing the data using the GPCM could provide the information needed for RQ 1(b).

Teachers’ raw scores in the four categories of complex systems ideas were first standardized on a continuum to reveal the difficulty level of each category. On this continuum of logit scale, 0 was set as the mean of the item or category difficulty parameter. On the positive direction of the scale, each increase indicated that the category of ideas was becoming more difficult; conversely, on the negative direction, each decrease signaled that the category was turning less difficult. Comparisons were then be
made using the item or category difficulty parameter in GPCM to determine the relative difficulties among the four ideas.

3.6.2.2 Part A in Perception questionnaire

Recall that in Part A of the Perception questionnaire, teachers ranked the complex systems ideas in order of their perceived conceptual difficulties. Specifically, they were given a list of the ideas and asked to put numbers 1 (least difficult) to 4 (most difficult) beside the ideas to indicate their relative conceptual difficulties. Figure 18 shows how a teacher responded to Part A. A mean score was calculated for each category of ideas for all the responses, and a relative ranking of their difficulty was obtained. This measure directly indicated the relative difficulty of the complex systems ideas from teachers’ perceptions. In other words, the category of ideas with the lowest mean score was perceived to be the least difficult to understand, while the one with the highest mean score the most difficult.

![Figure 18. Teacher’s response to Part A of Perception questionnaire](image)

3.6.2.3 Validity and reliability discussion

Validity and reliability of the ecology question in the UoCS questionnaire and the CSICM, and Part A of the Perception questionnaire is discussed in this section.
Ecology question and CSICM. How validity and reliability of the ecology question and the CSICM were ensured have been earlier discussed in section 3.6.1.6. Briefly, content validity of the ecology question and the CSICM has been ascertained in the previous study from which this assessment was derived (Goh et al., 2012). Face validity of the question was further supplemented with a pilot sample of four science teachers who did not find difficulty in understanding the question nor the instructions (Robson, 2002). Test-retest reliability of the ecology question was not done as there was a likelihood that the pilot participants would ‘learn’ from the initial testing (Feder, 2008; Trochim, 2006). As the responses were coded using the CSICM, an IRR test was needed to determine the manual’s reliability (Trochim, 2006). The IRR test on a random 20% of the scores showed a “substantial” to an “almost perfect” agreement (Landis & Koch, 1977) among three raters, with a mean kappa statistic of between 0.78 and 0.85 for the four categories, and 0.82 overall.

Part A of Perception questionnaire. Validity and reliability of the Part A of the Perception questionnaire was determined in the following ways. First, the question was vetted for face validity with the same four science teachers who helped pilot the UoCS questionnaire. These teachers were asked to complete the Perception questionnaire after they were introduced to complex systems. Subsequent interviews with these teachers after they completed the questionnaire revealed that the instructions and questions were clear. The pilot teachers were next asked to complete the Perception questionnaire again a week later (Feder, 2008; Trochim, 2006). Test-retest reliability for the Perception questionnaire was feasible because this questionnaire asked for the teachers’ views about
the difficulties in understanding complex systems ideas and their instructional practices; perceptions that were unlikely to be affected as a result of testing. Although this was a very small pilot size, it was worthwhile to note that there was perfect test-retest reliability for all four pilot teachers.

3.6.3 RQ 2a: To what extent complex systems ideas are conveyed during teachers’ instructional practices?

Investigating how systems-related topics are taught in regular science classrooms provides insights into the educational problem of students’ limited awareness in complex systems from a teacher perspective. The RQ was answered from the analyses of the responses to Part B of the Perception questionnaire and the transcripts of the video recordings. How the data was analyzed and how validity and reliability of the analyses were ensured is discussed next.

3.6.3.1 Part B of Perception questionnaire

The teachers were asked if complex systems ideas were incorporated into their teaching, and if so, what topics and how. This provided self-reported insights into their instructional practices. The teachers who indicated affirmatively provided descriptions on how these ideas were conveyed in their lessons. Figures 19 and 20 illustrate two teachers’ responses.
Figure 19. A chemistry teacher’s response to Part B of Perception questionnaire

2. Reflect on your teaching in the past six months, in particular of topics related systems, are these complex systems ideas incorporated in your teaching?

Yes / No (please circle)

If yes, please state the topic(s) in which this was done.

Topic(s): Chemical, Dynamic

and briefly describe how this was done.

Protein Chemistry

Figure 20. A biology teacher’s response to Part B of Perception questionnaire

Part B

2. Reflect on your teaching in the past six months, in particular of topics related systems, are these complex systems ideas incorporated in your teaching?

Yes / No (please circle)

If yes, please state the topic(s) in which this was done.

Topic(s): Cell Structure, Endocrine System

Genetic Basis of Variation,

and briefly describe how this was done.

Teaching the membrane system RER, SER, GA linking the structure/function of the organelle to protein synthesis and transport linking to DNA and Genomics

basically, presenting connection of concepts for the various topics.
The teachers’ responses were analyzed in the following two ways. First, the proportion of participants who indicated they have conveyed complex systems ideas was calculated for each science subject. This provided a straightforward comparison of the extent complex systems ideas were perceived to be conveyed among the biology, chemistry and physics classrooms.

Second, the topics or concepts mentioned by the teachers were classified according to the ‘A’ level science syllabi (SEAB, 2014). In Singapore, all science teachers teaching Grades 11 and 12 biology, chemistry and physics are guided by the science syllabi which list the topics and learning outcomes for each subject. Take the response in Figure 18a as an example, there were four topics implied or directly mentioned by the chemistry teacher. These topics were Chemical Bonding, Equilibria, Reaction Kinetics and Nitrogen Compounds. “Effective collision theory” and “Boltzmann distribution” are concepts in Reaction Kinetics topic while “protein chemistry” is a sub-topic within Nitrogen Compounds. In Figure 18b, there were three topics implied or mentioned by the biology teacher: Cellular Functions (“cell ultrastructure”), Cellular Physiology and Biochemistry (“endocrine system”) and Genetic Basis of Variation. A frequency table to illustrate the extent of the topics mentioned was then constructed.

3.6.3.2 Video transcripts

Video transcripts were analyzed to determine the extent – what and how explicit – complex systems ideas were translated in teachers’ instructional practice. The analysis of the video transcripts was very much guided by a microethnographic analytical technique (Erickson, 1996; Gee & Green, 1998).
According to the SAGE Dictionary of Social Research Methods (Jupp, 2006), microethnography refers to a method of “careful examination of communicative behaviors by studying the audible and visible details of human interaction and activity, as these occur naturally within specific contexts or institutions.” In the context of this study, microethnography refers to the study of the teachers’ instructional practices, as captured within the video transcripts, in minute detail through an up-close and exhaustive examination of how the teachers use language and other forms of visible communication to realize their curricula in the classrooms. Similar to other forms of discourse analysis guided by an ethnographic perspective, microethnography’s goal is to describe, explain and understand the local contexts so as to make meaning in depth (Mayring, 2000; Moses, 2012). Microethnography has been adopted to analyze classroom interactions from video recordings (e.g., Lemke, 1998; Oliveira et al., 2012; Pane, 2009). For instance, Oliveira and his team (2012) examine their case study science teachers’ speech in class through microethnography. They explain that this analytical technique, which focuses on the turn-by-turn unfolding of the speech being conducted through primarily through repeated inspection of the videos at smaller analytical levels such as episodes, is able to provide insight into teachers’ behaviors in the classroom contexts. In this study, the microethnographic analysis of the transcripts was similar to those done by other researchers. The analysis began by preparing the data into smaller units for analysis, coding the smaller units, and interpreting the codes; these procedures are described next.

Preparing the transcripts. The transcripts were prepared for analysis by first uploading them into a qualitative analysis and research software, *ATLAS.ti* version 7.1.3.
Segments of each transcript was then grouped and tagged into teaching episodes. A teaching episode is a unit of analysis, understood as a sequence of turns that spans a length of time focusing on a concept or an instructional activity (Gee, 2005). In the context of this study, each episode roughly described the teaching of one particular science concept, solving or addressing a problem or doing an instructional activity. It captured what and how the concept was taught, what examples or analogies the teacher used in the explanation, among other content-related aspects of their practice. Within an episode, the teacher might ask questions, show an applet or demonstration, explain the concept, get students to respond or present their solutions to a problem, and/or engage the class in a discussion. An episode ended when the teacher moved on to a new concept, problem or activity. There was usually more than one episode within a single 45-minute lesson. Depending on the concept, problem or activity, each episode took between 5 and 25 minutes. In all, 240 teaching episodes were identified from the transcripts, with an average of 40 per teacher. Although the number of teaching episodes observed varied slightly between 37 (Bill and Johnny) and 45 (Elly), the number of observation hours was fairly similar – 5 hours per teacher.

An example of a teaching episode is illustrated below. Willie, a chemistry teacher, was going through a question on molecular mixing with his students.

*Willie*  ... Just use these words, [refers to the list of helping words displayed on the projector screen] to explain why mixing [of the molecules] occur. [The words displayed are: collide, random, travel in straight line, speed, uniformly distributed, exchange energy and unpredictable. Accompanying the question is an animation of two enclosures containing one type of particles each. The enclosures are connected through a hole in the wall separating the enclosures. Initially, the particles are in their own enclosures but moving about randomly. After some time as the animation runs, the particles begin to mix.]

*Willie*  You don't have to use all the words, you can use other words. You can use other
forms of these words, ok? But use as many words as possible to describe why mixing
of molecules occur... And all your explanations should roughly be the same.
[Teacher pauses as students begin to work on the question]

Willie  Ok so after you are done right, you can just turn to your friend and just share your
answers. Turn to your friends and share your answer. Share with the person next to
you. No need to share in your groups, ok. And if you have any ideas that are
different, maybe you can just ask each other.
[Students begin to talk with one another. Teacher walks around to listen in. He asks a
pair for their responses and then picks up one of the students’ response and displays
it on a visualizer.]

Willie  This answer is from XXX. So it says here there is a contradicting term here. The
contradicting terms are these. The words ‘random’ versus ‘uniform’. ‘Random’
versus ‘uniform’ ok? Now for something that is random, we cannot do a prediction
right? Now in this case, can you agree that even though the movements are random,
we can still predict that end up eh, both of them [enclosures] have the same number
of particles. Right? So it says here [reads student's answer], the particles are
travelling, they collide and move in random directions, they move in seemingly
random directions. After exchange of energy, the paths of the molecules become
unpredictable. [teacher rephrases] The path of one particle becomes unpredictable
right? [back to student's answer] However, in the end, the molecules, [teacher adds
in] or the system of molecules, would still be uniformly distributed. So over here, it's
like you are not sure how they will move, but in the end you can still make a
prediction of the whole system. Do you find that intriguing? Quite intriguing right?
Even though individually, we cannot track the movement, this is the interesting part,
individually we cannot track the movement, but as a system, we can make a
prediction on what will happen. Right? So this is the thing I want you to appreciate.
Individually, it cannot track the movement but as a system we can predict what will
happen. Ok this is the thing I want you to understand. Thanks for sharing, XXX. And
if you haven't got this point, just write it down because it is really, really insightful
for XXX to write this.

In this teaching episode, Willie began by displaying a question on molecular mixing and
an animation illustrating what it means. He then had each student work on the question
individually before discussing with the student next to her. As Willie walked around to
listen in and facilitate their discussion, he picked up a response that he deemed
appropriate for sharing with the rest of the class. He proceeded to explain how the
unpredictable nature of particulate movements can lead to systemic property of uniform
distribution. The episode concluded with Willie summarizing the key points.

Coding the teaching episodes. The teaching episodes were next analyzed for the
complex systems ideas conveyed. The CSICM-B (see Appendix K), a modified version of
the *CSICM*, was used to guide the coding of the teaching episodes. In the *CSICM-B*, instead of three levels of complexity as found in the *CSICM*, the coding was distinguished into three nominal classifications for each category of ideas. “Level 0” was given when the ideas were not taught or implied. “Level 1” was given when the ideas were implied, that is, not directly taught. “Level 2” was given when the ideas or notions of these ideas were explicitly taught. This modified scheme was necessary because RQ 2a concerns the extent complex systems ideas are conveyed in the classrooms; it is not about the level of complexity of the ideas taught.

Coding for “Level 0” was relatively straightforward. Some episodes did not hint at complex systems ideas even though these are science lessons related to systems. There were also episodes that did not involve the teaching of scientific concepts at all. These typically showed teachers working out mathematical solutions of problems and explaining the interpretation of graphs. How the episodes were coded “Level 1” and “Level 2” for the various complex systems ideas are presented next.

(i) *Nonlinearity and non-determinism*: Episodes coded for the *Nonlinearity and Non-determinism* category would contain instructions regarding relationships among concepts and system components, feedback mechanisms, and stochastic or probabilistic phenomena. To be coded “Level 1,” the episode would need to show that the ideas were implicitly conveyed during the instruction. For instance, Johnny’s recap of a two-body collision contained the nonlinearity idea. He helped students recall the nonlinear force between the colliding bodies.

Johnny: *Remember the simulation [refers to a two-body collision simulation as he gestures with his hands], bang! [and the ‘two bodies’ rebound]. The force applied increases*
Johnny did not explicitly mention about nonlinearity, but the non-constant retarding force he alluded to is a result of the deformation of the material during collision. For an elastic collision, a larger deformation results in a stronger retarding force, in turn causes the two bodies to “rebound” and reduces this retarding force. This feedback loop (i.e., large incident force $\rightarrow$ deformation $\rightarrow$ increases retarding force $\rightarrow$ smaller incident force $\rightarrow$ less deformation $\rightarrow$ less retarding force) encapsulates the idea of nonlinearity in this two-body system.

Willie’s episode on diffusion of particles illustrated a “Level 2” coding on teaching of non-determinism. He used a NetLogo simulation of gas particles to link diffusion to particulate movements. He started with a 1-particle simulation, moving on to 2, 16 and finally 1000-particles. The following excerpt describes the moment when Willie was just transiting from 1 to 16 particles in the simulation.

*Willie* 
What would happen to the path of the particle after a long while? If I asked you to draw the pattern, would you be able to draw it? [Some students shake their heads] Can’t right? Because there are just too many to keep track of. It’s too unpredictable. [Simulation has 16 particles in a big box, it has a trace on the path of one particle, the path is erratic in nature]

Willie was explicit in conveying the idea of non-determinism through the unpredictable movements of particles. Prior to this episode, Willie illustrated how the model of kinetic theory of particles describes that a single particle move in a straight line until it collides with the system boundaries. Here, he extended the idea to include many particles and due
to multiple collisions, the particles rebounded in all directions too often that their paths become unpredictable.

(ii) Open and dynamic nature: Episodes coded for the Open and Dynamic Nature category would contain evidence that the teachers brought up notions of the system being in constant state of flux, and highlighted the less-obvious components within or external conditions outside of the system affecting its outcomes. To be coded “Level 1,” the episode would need to show that the ideas were implicitly conveyed during the instruction. For instance, Casey described the influence of the environment on the resistance of thermistors.

Casey [Draws an open circuit that includes an ammeter, a voltmeter and a cell] You have ammeter, a voltmeter, and then you have your thermistor... [draws in thermistor] ... drawn like this. Here's the difference. A thermistor reacts to what? [student responds] Change in... temperature of the surrounding.

Casey checked her students’ understanding on thermistors. The effect of environmental conditions on electrical components is related to the idea of open nature because through these electrical components and their changes, the overall resistance of the electrical system is affected. In this episode, even though Casey talked about the effect of temperature on thermistor, he was not explicit about the importance of the external environment on the circuit as a system.

Elly’s episode on speciation depicted how a “Level 2” coding could be given. She highlighted that through differential selection pressures, the same species might evolve into different species over a period of time.
... Over time, over billions of generations, after many rounds of selection, and differential survival, and differential reproduction, this will be roughly the gene pool for the species on XXX's island. Gene pool consists of yellow and black alleles. Over time, YYY's island, the population on YYY's island will look roughly like that. [holds up beaker with no yellow] Gene pool is red and black alleles... Over time we see that the gene pool becomes very different. And this will eventually lead to speciation... This will lead to speciation over a long time.

Elly was explicit in teaching the idea of dynamic nature, even though the term ‘dynamic’ was not used. The idea was expressed through the repeated emphasis on changes taking place “over billions of generations, after many rounds of selection, and differential survival, and differential reproduction… the gene pool becomes very different.” Being dynamic means the system is in a constant state of flux for a long time.

(iii) Emergence and self-organization: Episodes coded for the Emergence and Self-organization category would contain evidence of teachers talking about how large-scale systemic patterns can be caused by localized behaviors, or how the systemic patterns may be spontaneously produced. For a “Level 1” coding, the episode would show that these ideas were implicitly conveyed during the instruction. For instance, Bill talked about product chirality (i.e., mirror images but not superimposable) arising from reaction mechanisms.

Bill This one [refers to the inverted product] is chiral if it's hundred percent of this product. The sample is optically active. Okay? If I have hundred percent of this product [refers to the non-inverted product], it is also optically active. But if I have a mixture, fifty-fifty, the mixture of the 2 molecules will give me a sample, which is optically not active.

Bill explained that the proportion of different chiral products can affect their optical activity. While the individual products may be optically active in a pure sample, a racemic mixture can give a sample that is not. This optical activity is an emergent
property. His use of the word ‘sample’ hinted of the need to differentiate between localized orientations of the products and systemic optical property of the sample.

Jeremy’s episode depicted how the ideas of emergence and self-organization can be coded “Level 2.” In this episode, he described the semi-conservative replication process of DNA.

Jeremy Helicase. As the helicase binds, it will start to unwind correct? So as it unwinds, it breaks the hydrogen bonds and forms a replication… bubble. So the bubble will get bigger and bigger right? [truncated] So now, this template strand and this template strand are exposed right? So the bases are now exposed. So what happens? The DNA nucleotides will fit in, just like that, the free nucleotides will now base-pair, so [they] will base-pair. The G-nucleotide, the T-nucleotide will base-pair, just like that.

The pairing of free nucleotides with their complementary base pairs on the template strands to become new DNA molecules suggests non-intentional or self-organized arrangement of components to form new structures. Jeremy’s repeated use of the word “base-pair” and “just like that” referred to the idea of self-organization, even though the exact term was not used.

(iv) Decentralization: Episodes coded for the Decentralization category would contain evidence of teachers conveying the notion that the system is affected by more than two components, factors or causes and not simply one key component, factor or cause. For a “Level 1” coding, the episode would show how these ideas were implicitly conveyed during the instruction. For instance, Bill compared the differential reactivity of ketone and aldehyde.

Bill [Which carbonyl] functional group is more reactive towards nucleophilic addition reaction? Ketone? Aldehyde? Aldehyde more reactive? Yes you are right. Reasons why aldehydes are more reactive.

Student More space

Bill More space okay so… we are talking about steric hindrance. Okay. We must realize this whole thing [trigonal planar of aldehyde] is flat right. So when this whole thing is flat, the molecule is flat on paper… [truncated]… So when the nucleophile comes
Okay? So this group \[\text{CH}_3\] in aldehyde, this group \[\text{CH}_3\] in ketone, we consider them bulky groups compared to the \(H\) here [aldehyde]. Okay, so this is a quite a small atom right? While this \[\text{CH}_3\] is like many times bigger than this one \([H]\) so we consider this \[\text{CH}_3\] to be a bulky group. If the whole thing is flat, thus \[\text{CH}_3\] is acting like a very ball that is preventing the nucleophile from attaching this \(C\) [of aldehyde].

Bill explained why ketone is more reactive than aldehyde toward a nucleophilic addition reaction. The multiple factors involved, that is, the planar arrangements of aldehyde and ketones, the sizes of the \(\text{CH}_3\) (methyl) group and \(H\) (hydrogen) atom, and the steric hindrance caused by these groups, need to be considered in order to explain their relative reactivity. Through his explanation, he hinted that there was not just one key factor determining the relative reactivity.

Jeremy’s episode on the DNA replication process illustrates how the idea of decentralization can be coded a “Level 2.” He reviewed the complex process of replication.

Jeremy  Ok, so what happens when the DNA polymerase reaches the primer? The primer will have to be removed right? Because it is a RNA primer right? So you want to remove this, ok? [truncated] DNA polymerase III will be replaced by DNA polymerase I. That will remove the RNA primer right? Ok? And then extend. Ok, so now you have this already. You have this fragment, and this fragment, and then you have a third enzyme called DNA ligase that will join the two fragments together. So what about the enzymes? You have four. You have your DNA helicase, you have your primase, DNA polymerases III and I, and you have your DNA ligase. So 1, 2, 3, 4 enzymes.

Replication is a complex process because there are many enzymes and other molecules involved. Jeremy took time to elaborate the process with an emphasis on the roles of the enzymes and molecules. He concluded by reminding the students of the four enzymes...
responsible during DNA replication. Through this explanation of the crucial roles each component play, decentralization was explicitly taught.

Presenting the results. After coding the episodes, a frequency table of the results was produced. A mean score for each category of complex systems ideas was also calculated for each teacher based on the results to illustrate the extent complex systems ideas were translated in their instructional practices. A mean score of less than 0.66 meant that the particular idea was mostly not conveyed at all. A mean score of 0.66 to 1.33 meant that the idea was only taught explicitly at times or largely implied through the teaching of other scientific concepts. A mean score of more than 1.33 meant that the idea was often taught explicitly. Table 12 summarizes the interpretation of the mean scores.

Table 12

<table>
<thead>
<tr>
<th>Interpretation of mean scores on CSICM-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.66</td>
</tr>
<tr>
<td>0.66 – 1.33</td>
</tr>
<tr>
<td>&gt; 1.33</td>
</tr>
</tbody>
</table>

3.6.3.3 Validity, reliability and trustworthiness discussion

Validity and reliability of Part B of the Perception questionnaire and the video transcripts is discussed in this section. How inter-rater reliability is established in the use of CSICM-C to code the teaching episodes is also described.

Part B of Perception questionnaire. Ensuring the validity and reliability of Part B of the Perception questionnaire was similar to that for Part A of the same questionnaire (see section 3.6.2.3) and is briefly reiterated here. Part B was also vetted for face validity with the same four science teachers. Interviews with these teachers after they completed the questionnaire revealed that the instructions and questions were clear. These pilot
teachers were asked to complete the Perception questionnaire again for test-retest reliability check a week later (Feder, 2008; Trochim, 2006), and as in the case of Part A, there was perfect test-retest reliability for Part B from all four pilot teachers.

*Video transcripts.* In his book *Research Design*, Creswell (2009) lists eight strategies for establishing trustworthiness with qualitative data analysis. He recommends that researchers choose at least two of the eight listed for qualitative data. This portion of the current research involves three of them. They include (i) prolonged and persistent observation in the field, (ii) rich, thick description and (iii) member checks; these are addressed in the following ways.

First, building trust with the participants and learning the culture involved immersing oneself in the field for long periods of time. In this study, a total of 28 hours was spent recording the lessons, that is, 6 periods of 45 or 50 minutes for each teacher. While this amount of time was certainly insufficient for the research to be considered ethnographic in nature – it was not meant to be one, this deliberately-planned time length was adequate to capture the formal instruction of a single science topic in its entirety.

Second, a rich and thick description of the phenomenon allows readers to make informed decisions regarding the transferability of the findings. In this study, the video transcripts detailed in verbatim the exact on-goings during the lessons, providing a rich, thick and exact data about teachers’ instructional practice (Derry, 2007; Jewitt, 2012).

Third, Creswell considers soliciting participants’ views of the credibility of the findings and interpretations to be the most important strategy for establishing the trustworthiness. In this research, interpretations of the data were cross-checked with the
teachers during the interviews for their judgment on the accuracy and credibility of the account. All members gave their approval to the interpreted data.

*CSICM-B.* As the video transcripts were coded using the *CSICM-B*, it is also necessary to discuss the validity and reliability of the categorization manual. The *CSICM-B* is a simpler version of the *CSICM*. The explanations to illustrate each category of complex systems ideas were exactly the same as those found in the *CSICM*. A discussion on the validity of the *CSICM* has taken place in section 3.6.1.5, so it is briefly repeated here. Validity of the *CSICM-B* primarily concerns the correct depiction of the complex systems ideas in the categorization manual to guide the coding. All two versions of the *CSICM* have been adapted from earlier peer-reviewed studies (e.g., Jacobson, 2001; Yoon, 2008). An advanced doctoral student, who was knowledgeable in the subject matter of complex systems, was involved in the development of both versions of *CSICM*.

An IRR test was performed on *CSICM-B* in coding the video transcripts. There are four stages to this IRR process, namely: (i) selection of raters; (ii) training of raters; (iii) scoring of responses; and (iv) results of IRR test.

(i) *Selection of raters:* Three raters (including me) were involved in the IRR test. Raters A and B who helped with the IRR test for the *CSICM* did the same for the *CSICM-B*. Information about the raters can be found in section 3.6.1.6.

(ii) *Training of raters:* Training of the raters in the use of the *CSICM-B* was done on different days from their training in the use of *CSICM*. Lesser time was spent on training of *CSICM-B* as the raters, by then, were quite familiar with the description of each category of complex systems ideas. The raters were
first led through the scoring definitions for each category. Exemplars were read aloud and the complex systems ideas contained within them were explained. The raters were then asked if they had any questions. Following their verbal agreement that the scoring codes were clear to them, they were progressively given ten other teaching episodes to score. As before, a think-aloud strategy was used to better understand the raters’ decision-making processes (Lasky, 2012; Lochhead, 2001). After scoring each episode, the raters were asked to talk about the rationale for giving their particular score for each category of complex systems ideas. I then stated my score and explained why I agreed or disagreed with them. Finally, the raters’ difficulties in interpreting the given teaching episode were deliberated and improvements to CSICM-B were made.

(iii) Scoring of teaching episodes: The scoring of the teaching episodes by the two raters was performed immediately after their training; however the actual coding took over two sessions. 30 randomly selected teaching episodes (more than 10% of the teaching episodes) were used for IRR. The raters spent about five to ten minutes for each episode, and coded all four categories of complex systems ideas at the same time. They rated the episodes independently in my presence. I also rated the 30 teaching episodes independently. After the scores were assigned, they were keyed into a spreadsheet for subsequent analysis.

(iv) Results of IRR tests: As explained in section 3.6.1.5, the IRR test suggested by Light (1971) for a fully-crossed design (i.e., a subset of the respondents
rated by a same set of coders) with more than two raters was used to analyze the scores. The mean kappa statistic obtained for the 30 teaching episodes was between 0.72 and 0.82 for the four categories and 0.76 overall, which could be qualified as “substantial agreement” (Landis & Koch, 1977) Table 13 shows the breakdown of the IRR analyses. In sum, the CSICM-B was found to be reliable in analyzing the teaching episodes. Subsequently, my scores were used as the data for RQ 2a.

Table 13

Average kappa statistic for IRR Test on the use of CSICM-B to code teaching episodes

<table>
<thead>
<tr>
<th>Category</th>
<th>Symmetric Measures</th>
<th>Raters</th>
<th>Value</th>
<th>Asymp. Std. Error</th>
<th>Approx. T</th>
<th>Approx. Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A (Nonlinearity and nondeterminism)</strong></td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.683</td>
<td>.125</td>
<td>4.699</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>N of Valid Cases = 30</td>
<td>A and me</td>
<td>.919</td>
<td>.075</td>
<td>5.967</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.605</td>
<td>.128</td>
<td>4.229</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong> Kappa</td>
<td>A, B, and me</td>
<td>.736</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>B (Open and dynamic nature)</strong></td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.683</td>
<td>.109</td>
<td>5.175</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>N of Valid Cases = 30</td>
<td>A and me</td>
<td>.740</td>
<td>.097</td>
<td>5.908</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.738</td>
<td>.095</td>
<td>5.962</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong> Kappa</td>
<td>A, B, and me</td>
<td>.720</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>C (Emergence and self-organization)</strong></td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.749</td>
<td>.100</td>
<td>5.892</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>N of Valid Cases = 30</td>
<td>A and me</td>
<td>.696</td>
<td>.108</td>
<td>5.436</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.746</td>
<td>.102</td>
<td>5.743</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong> Kappa</td>
<td>A, B, and me</td>
<td>.730</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D (Decentralization)</strong></td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.741</td>
<td>.101</td>
<td>5.785</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>N of Valid Cases = 30</td>
<td>A and me</td>
<td>.948</td>
<td>.051</td>
<td>7.253</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.792</td>
<td>.094</td>
<td>6.083</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong> Kappa</td>
<td>A, B, and me</td>
<td>.827</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>All categories</strong></td>
<td>Measure of Agreement, Kappa</td>
<td>A and B</td>
<td>.725</td>
<td>.053</td>
<td>11.064</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>N of Valid Cases = 120</td>
<td>A and me</td>
<td>.828</td>
<td>.044</td>
<td>12.490</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B and me</td>
<td>.736</td>
<td>.051</td>
<td>11.195</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td><strong>Average</strong> Kappa</td>
<td>A, B, and me</td>
<td>.763</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. Not assuming the null hypothesis.
b. Using the asymptotic standard error assuming the null hypothesis.
c. Mean kappa statistic for three raters (Light, 1971)
3.6.4 RQ 2b: What is the relationship between science teachers’ understanding of complex systems and their instructional practices?

RQ 2b investigates the relationship between science teachers’ instructional practice and their complex systems understanding. Establishing this relationship is essential because this present research rests on the proposition that without a good understanding of complex systems, science teachers will not be able to convey the salient complex systems ideas (see section 2.2.3). RQ 2b is answered from two levels of analyses. The first level relied on the survey responses from the large and representative group of teachers. The results of the ecology question in the UoCS survey were associated with those of the Part B in the Perception survey. The second level was more qualitative in approach. The six teachers’ responses to the tests of complex systems understanding in the UoCS questionnaires were examined against their instructional practices. In combination, these two levels of analyses would provide both a broad picture and an in-depth insight of the possible relationship between teachers’ complex systems understanding and their instructional practice. How the data was analyzed is described in the following sections before a discussion on the validity and reliability of the data analysis.

3.6.4.1 Association between results of ecology question and Part B of Perception survey

The analyses of the responses to the ecology question in the UoCS questionnaire and Part B of the Perception questionnaire have been explained in sections 3.6.1 and 3.6.3. Briefly, the ecology question of the UoCS questionnaire asked teachers to explain the possible effects of geese migrating to a park ecosystem. Their responses were scored
using the CSICM. Part B of the Perception questionnaire asked teachers if they incorporated complex systems ideas into their practice and how. The relationship between teachers’ complexity scores in the ecology question (see section 3.6.1.5) and their indication of incorporating complex systems ideas in their instructional practices was determined in the following way.

First, scores in each category of ideas were first summed to provide a total score for each teacher. For instance, if a teacher’s response is coded as Levels 1, 3, 1, and 2 for the four categories of ideas using the CSICM, the total score would be 7. A total score of 4 - 6 was classified as having a ‘clockwork’ perception; a total score of 7 to 9 as having a ‘somewhat complex’ perception; and a total score of 10 to 12 as having a ‘complex’ perception. These formed the overall UoCS perception for each teacher. Next, each teacher’s response (i.e., yes or no) on whether he or she has incorporated complex systems in their practices in the past six months was compiled together with their overall UoCS perception (i.e., total score for the ecology question).

Finally, the null hypothesis that the teachers’ overall UoCS perception and their indications of incorporating complex systems ideas in their practices were independent was tested. For this analysis, a chi-square test for independence was conducted and the significance level was set at 0.05. Cramer’s V test statistic was used to test the strength of association (Cramér, 1999; Franke, Ho & Christie, 2012; Steinberg, 2011). In short, the result would tell us if teachers with better understanding of complex systems reported higher incidence of conveying these ideas in their classroom practice.
3.6.4.2 Comparison between ecology question results and video transcripts

The analyses of six teachers’ responses to the various tests in the UoCS questionnaire and their video transcripts have been explained in earlier sections 3.6.1 and 3.6.3. How these two sets of data were used to answer RQ 2b is described here.

In order to have a better appreciation of the extent each teacher understood complex systems ideas, it was necessary to examine how they performed on the various tests in the UoCS questionnaire. Findings from RQ 2a, that is, the extent the complex systems ideas were conveyed in these six teachers’ instructional practices, were then qualitatively compared with their understanding of the various ideas to determine if there is a relationship between their understanding of complex systems and instructional practices. A narrative was written to describe this relationship.

3.6.4.3 Validity, reliability and trustworthiness discussion

Validity and reliability of the ecology question, Part B of the Perception questionnaire, and the use of CSICM and CSICM-B for coding the responses have been adequately discussed in earlier sections 3.6.1 and 3.6.3; the discussion will not be repeated here. However, it is necessary to discuss the validity of the comparative methods in analyzing the relationship between teachers’ understanding and practice.

Chi-square test of independence. The assumptions for using a chi-square test were met: each observation was independent of all others; the clusters were randomly-sampled and no clustering effect was found (see section 4.2.5); the sample size was adequately large ($N = 84$); no more than 20% of the expected counts in each cell in the chi-square matrix were less than 5; and all individual expected counts are 1 or greater (Yates, Moore
As one of the variables was nominal (i.e., ‘yes’ or ‘no’) and the other (i.e., overall UoCS perception or total score for ecology question) was ordinal, Cramer’s $V$ was the appropriate test statistic to test the strength of association (Cramér, 1999; Franke et al., 2012; Steinberg, 2011).

**Qualitative comparison.** Creswell (2009) recommends that researchers choose at least two of the eight strategies in establishing trustworthiness for qualitative data analysis. This portion of the current study involves four of them. They include (i) prolonged and persistent observation in the field, (ii) rich and thick descriptions, (iii) member checks, and (iv) triangulation. The first three have been addressed in in section 3.6.3.3. The fourth criterion, Creswell explains, involves having different sources to provide corroborating evidence. In this qualitative comparison, the analyses of the video transcripts and the test scores from the three tests of complex systems understanding of the six teachers provided the corroboration needed to establish trustworthiness.

**3.6.5 RQ 3: What are the teachers’ reasons behind the perceived difficulties in understanding and teaching these complex systems ideas?**

Finding out why science teachers may (or may not) find difficulty in understanding and teaching complex systems ideas can clarify the challenges and issues that may need addressing in future efforts to improve the learning and instruction of complex systems. RQ 3 is answered from the analyses of the written responses to Part C of the Perception questionnaire and the teacher interviews. How the data was analyzed is described in the following sections before a discussion on the validity and reliability of the data analysis.
3.6.5.1 Perception questionnaire

Recall that in Part C of the post-workshop questionnaire, teachers were asked if they perceived complex systems ideas difficult to understand, and why. The list of reasons as explained earlier were developed based on a review of the literature and expanded subsequently after a brainstorming process. They were also free to add reasons that were not listed. Unfortunately, as the actual sample size was small (i.e., less than 100 even though the targeted sample was supposed to be more), factor analysis could not be performed on the selected reasons (Ferguson & Cox, 1993; MacCallum et al., 1999). Instead, descriptive statistics were used to provide insight on what the reasons may be.

3.6.5.2 Teacher interviews

The semi-structured interviews aimed to find out the reasons for the perceived difficulties teachers face in understanding and teaching complex systems (RQ 3). A thematic analysis was performed to analyze these interviews for the reasons (Miles & Huberman, 1994; Smith & Osborn, 2003). Thematic analysis involves searching through the qualitative data to identify themes or in this case, reasons for difficulties teachers face in understanding and teaching complex systems. A theme is akin to a cluster of linked reasons conveying similar meanings (Berkowitz, 1997; Patton, 2002). There are generally three distinct phases in this analysis (Elliott & Timulak, 2005).

First, the data was prepared for analysis. All interviews were transcribed in verbatim and subsequently loaded into the ATLAS.ti version 7.1.3 software to facilitate the analysis. Each line of utterance served as a unit of analysis for indexing or coding. Such line-by-line coding allowed the data to be closely scrutinized. Next, an overall
organizing structure was introduced to help make initial sense of the data. As I already had some broad ideas of what the reasons might be based on the review of the literature (see sections 2.3.4 and 3.5.2), broad domains of curriculum, ontology, learning and beliefs were used to ‘park’ the units of analysis.

Following this domain grouping, the units were categorized. This was the most intensive part of the analytical process. Each unit was meticulously mined for key points that related to the reasons, and descriptors were assigned. Similar descriptors were then grouped as a first level of consolidation. From these groupings, a second level of consolidation was undertaken where categories of reasons were formed. These categories formed the themes of reasons behind teachers’ difficulty in understanding and teaching complex systems ideas.

Creation of categories was an interpretive process on my part (or any qualitative researcher) in which on the one hand, I had to respect the data and use category labels close to the language of the teachers, and on the other hand, the ideas for the categories were derived from my knowledge of this field (Smith & Osborn, 2003). In this sense, the thematic analysis, like other inductive analyses, emphasizes that the analytical process is dynamic with the researcher playing an active role in the process. It is therefore necessary to reflect upon and reveal my personal assumptions. This, and other issues of trustworthiness, is discussed next.

3.6.5.3 Validity, reliability and trustworthiness discussion

Validity and reliability of Part C of the Perception questionnaire and trustworthiness of the qualitative interview data is discussed in this section.
Perception questionnaire. Ensuring the validity and reliability of Part C of the Perception questionnaire was similar to that for Parts A and B of the same questionnaire (see sections 3.6.2.3 and 3.6.3.3) and is briefly reiterated here. The question in Part C of the Perception questionnaire was vetted for face validity with four science teachers. Interviews with these teachers after they completed the questionnaire revealed that the questions were clear and answerable. These pilot teachers were asked to fill in the Perception questionnaire again for test-retest reliability check a week later (Feder, 2008; Trochim, 2006). Although this was a very small pilot size, there was near perfect test-retest reliability for all four pilot teachers; one of the teachers chose three reasons, instead of his original four, during the retest.

Interview data. Four aspects of Creswell’s (2009) criteria for establishing trustworthiness of qualitative data analysis were fulfilled. First, there has been prolonged and persistent immersion in the field as a total of 30 hours was spent video-recording the lessons (between 5 to 6 lessons per teacher). These extended hours excluded the two additional lessons per teacher prior to actual recording. This facilitated honest responses from the teachers during the interviews as rapport was built during the immersion. Second, all teacher conversations were transcribed verbatim, providing rich, thick and exact descriptions of what they said. This allowed the teachers’ interviews to be captured in context, making subsequent interpretations more valid. Third, interpretations of the interview data were cross-checked with the teachers after data analyses to ensure accuracy of the interpretations. The teachers were asked if they agreed – and all did – with the findings. Fourth, the bias the researcher brought to the research was clarified.
Aside from what I gathered from the literature review about why complex systems learning and instruction might be difficult, I was also aware that I had prior assumptions about the state of complex systems learning and instruction in Singapore science classrooms based on my experiences as a science teacher in a local high school. I had a hunch that most teachers did not consciously incorporate complex systems into their instructional practices because the existing science syllabi and national assessments did not feature complex systems prominently. I was mindful not to let this personal bias influenced my interpretation of the interviews by using the teachers’ voices as much as possible when the themes were generated.

3.7 Summary: Logic Model

This chapter is summarized with a logic model in Table 14. This model presents how the strategies of the study logically follow from the RQs, so as to yield a focused data set from which to analyze and make conclusions. Great care has been undertaken to ensure that the research design and methods of data collection and analysis are systematic in addressing the gaps in the literature, and committed to ascertaining the validity, reliability and trustworthiness of the findings.
### Table 14

**Logic model**

<table>
<thead>
<tr>
<th>Needs</th>
<th>Research Questions</th>
<th>Data collection</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insufficient large-scale research that looks at the extent science</td>
<td>RQ 1a: To what extent do science teachers understand complex systems?</td>
<td>UoCS questionnaire with three tests of complex systems understanding</td>
<td>Descriptive statistics on the scores science teachers get for each complex systems idea</td>
</tr>
<tr>
<td>teachers understand about complex systems.</td>
<td></td>
<td></td>
<td>Further breakdown of descriptive statistics by demographic data</td>
</tr>
<tr>
<td></td>
<td>A better understanding of which complex systems ideas are more difficult can inform</td>
<td>RQ 1b: Are there certain complex systems ideas that are more difficult than</td>
<td>Relative difficulty of ideas is determined using GPCM</td>
</tr>
<tr>
<td></td>
<td>professional development</td>
<td>others for these teachers to understand, and if so, what are these??</td>
<td>Self-reported ranking on relative difficulty</td>
</tr>
<tr>
<td></td>
<td>Teachers’ understanding of complex systems ideas must not only be explored</td>
<td>RQ 2a: To what extent complex systems ideas are conveyed during science</td>
<td>Proportion of teachers who indicate affirmatively that they are conveying complex systems ideas in their lessons</td>
</tr>
<tr>
<td></td>
<td>from a knowledge aspect, but also how that understanding is used in practice.</td>
<td>teachers’ instructional practices?</td>
<td>Descriptive statistics on the coding of teaching episodes</td>
</tr>
<tr>
<td></td>
<td>Relationship between science teachers’ understanding of complex systems and their</td>
<td>RQ 2b: What is the relationship between science teachers’ understanding of</td>
<td>Chi-square correlation between understanding of complex systems scores and perceived instruction of complex systems</td>
</tr>
<tr>
<td></td>
<td>instructional practices has not been established.</td>
<td>complex systems and their instructional practice?</td>
<td>ideas</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Qualitative comparison between teachers’ understanding of complex systems ideas and their classroom instruction of</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>systems-related topics</td>
</tr>
<tr>
<td></td>
<td>A more systematic investigation of the reasons behind difficulties in understanding</td>
<td>RQ 3: What are the reasons behind their difficulty in understanding and teaching these complex systems ideas?</td>
<td>Descriptive statistics on the reasons chosen.</td>
</tr>
<tr>
<td></td>
<td>and teaching complex systems ideas so that professional development can address</td>
<td></td>
<td>Reasons obtained from thematic analysis.</td>
</tr>
<tr>
<td></td>
<td>these difficulties.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4 Results

4.1 Chapter Overview

In this chapter, the results of the data analysis are organized according to the RQs:

- Section 4.2: Using statistical analyses of the three tests of complex systems understanding in the UoCS questionnaire with further breakdown by the available demographic information of the teachers, the extent the science teachers understood complex systems ideas was described.

- Section 4.3: Using GPCM analysis of the scores on the ecology question in the UoCS questionnaire and the self-reported ranking on the relative difficulty of the complex systems ideas in the Perception questionnaire, the relative difficulty was determined.

- Section 4.4: Using statistical descriptions of the proportion of teachers who indicate affirmatively in the Perception survey that they are conveying complex systems ideas in their lessons and the coding of the teaching episodes of the six teachers video-recorded, the extent – what and how explicit – complex systems ideas were conveyed in their regular science classrooms was ascertained.

- Section 4.5: Using chi-square correlation between science teachers’ scores in the ecology question and their perceived instruction of complex systems ideas from two surveys, and qualitative comparison between the six teachers’ scores in the ecology question and their classroom instruction of systems-related topic,
the relationship between teachers’ complex systems understanding and their instructional practices was determined.

- Section 4.6: What are the reasons? Using descriptive statistics from the Perception survey and thematic analysis of the interviews, the reasons behind their difficulty in understanding and teaching these complex systems ideas were systematically derived.

4.2 RQ 1a: To what extent do science teachers understand complex systems ideas?

The three tests of complex systems understanding in the UoCS questionnaire provided the data to investigate the extent 11th and 12th grades science teachers understand complex systems ideas. The findings generally revealed that 11th and 12th grades science teachers had some understanding of complex systems ideas, but this understanding was inadequate and not comprehensive. The participants appeared to have a complex understanding of decentralization, a somewhat complex understanding of nonlinearity and non-deterministic, and emergence and self-organization, and an isolated and static perception when interpreting complex systems.

4.2.1 Nonlinearity and non-determinism

The Web-like Causality Index scores from the causal mapping exercise and the scores from the Nonlinearity and Non-determinism category of the open-ended ecology question are reported here. From both analyses, the teachers appeared to have a somewhat nonlinear and non-deterministic view of complex systems.
There were a total of 87 responses (i.e., 3 missing values with listwise deletion) to the causal mapping exercise. The mean Web-like Causality Index score for the science teachers was 0.48 ($SD = 0.27$). In other words, the teachers had a somewhat nonlinear and non-deterministic perspective. Figure 21 shows the spread of the Web-like Causality Index scores.

![Web-like Causality Index scores](image)

Figure 21. Web-like Causality Index scores

There were a total of 89 responses (i.e., 1 missing value with listwise deletion) to the ecology question. Using the CSICM to code these responses, the mean level of complexity for nonlinearity and non-determinism ideas was 2.06 ($SD = 0.71$), that is, the teachers had a somewhat complex view of these ideas. Figure 22 shows the spread of the scores.
Figure 22. Nonlinearity and non-determinism scores using CSICM

4.2.2 Open and dynamic nature

The number of feedback loops in the causal mapping exercise and the scores from the Open and Dynamic Nature category of the ecology question are reported here. From both analyses, the teachers did not appear to perceive complex systems as open and dynamic in nature.

62% of the 87 maps (i.e., 3 missing values with listwise deletion) did not feature feedback loops, 23% had one or two loops and only 15% had more than two loops. In other words, slightly less than two-thirds of the teachers had an isolated and static perception of the socio-scientific issue. Figure 23 show the frequency of the number of feedback loops.
Using the CSICM to code the 89 responses to the ecology question, the mean level of complexity for the open and dynamic nature ideas was only 1.65 ($SD = 0.66$), that is, the teachers appeared to have an isolated and static perspective. Figure 24 show the spread of the scores.

**Figure 23.** Frequency of number of feedback loops

**Figure 24.** Open and dynamic nature scores using CSICM
4.2.3 Emergence and self-organization

The proportions of complex belief statements chosen in the visualization exercise and the scores from the *Emergence and Self-Organization* category of the open-ended ecology question are reported here. From both analyses, the teachers appeared to perceive complex systems’ patterns and behaviors as somewhat emergent and self-organized.

There were a total of 84 responses (i.e., 6 missing values) to the visualization exercise. The mean proportion score was 0.57 ($SD = 0.21$). In other words, on average, slightly more than half of the statements chosen reflect an emergent and self-organized view to the birds flocking phenomenon. Figure 25 show the spread of the proportion scores.

*Figure 25. Proportion of chosen statements that reflect emergence and self-organization beliefs*
Using the CSICM to code the responses to the ecology question, the mean level of complexity for the emergence and self-organization ideas was 2.16 (SD = 0.58), that is, having a somewhat complex view. Figure 26 show the spread of the scores.

![Histogram](image)

**Figure 26.** Emergence and self-organization scores using CSICM

### 4.2.4 Decentralization

The proportion of teachers who had selected the decentralized ant-foraging model in the visualization exercise and the scores from the *Decentralization* category of the open-ended ecology question are reported here. From both analyses, the teachers appeared to perceive complex systems' patterns and behaviors as decentralized.

About 73% of the 84 teachers chose the decentralized model of ant foraging behavior. Figure 27 shows the distribution.
Figure 27. Distribution of decentralized and centralized responses

Using the CSICM to code the responses to the ecology question, the mean level of complexity for the decentralization idea was 2.42 ($SD = 0.70$), that is, having a somewhat complex view. Figure 28 show the spread of the CSICM scores.

Figure 28. Decentralization scores using CSICM
4.2.5 Demographics

The demographics information was used to determine if there is/are (i) clustering effect by schools the participants were teaching, (ii) difference between participants who indicated they have prior awareness of complex systems and those who did not, and (iii) differences across participants teaching the three science subjects on their complex systems understanding.

**Clustering effect.** Mentioned earlier in section 3.6.1.5, as the schools were cluster-sampled, it was necessary to see if there were significant differences in their complexity understanding between schools and within schools as this may lead to bias in the results (Kaplan & Keller, 2011; Kerry & Bland, 1998). This was done by first standardizing the various test scores and summing them to produce a total complexity score for each participant. The Shapiro-Wilks test for normality indicated the distribution of total complexity scores was normal ($p = 0.85$). To determine clustering effect, this total complexity score was analyzed using one-way ANOVA with school as the factor. Homogeneity of variance was also not significant, Levene’s $F(5, 81) = 0.92, p = 0.47$, indicating that the assumptions underlying the application of ANOVA were met. An alpha level of 0.05 was used for subsequent analysis. The one-way ANOVA of total complexity scores revealed there was no significant difference in the means ($F(5,81) = 0.61, p = 0.69$). In other words, it is unlikely that there was a school clustering effect on this teacher data.

**Difference between participants with prior and no complexity awareness.** The normally distributed total complexity scores for the participants were used in a one-way
ANOVA to examine whether the scores were a function of teachers’ prior awareness in complex systems. Homogeneity of variance was not significant, Levene’s $F(1, 85) = 0.66, p = 0.42$, indicating that the assumption underlying the application of ANOVA was met. An alpha level of 0.05 was used for subsequent analysis. The one-way ANOVA of the total complexity scores by their prior awareness (see Table 15) produced significant differences in the means ($F(1,85) = 7.18, p < 0.01$). This means teachers who had prior awareness of complex systems had a significantly higher total complexity score compared to teachers without this prior awareness. In other words, teachers with prior awareness of complex systems scored better on the tests.

Table 15

<table>
<thead>
<tr>
<th></th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between groups</td>
<td>42.032</td>
<td>1</td>
<td>42.032</td>
<td>7.184</td>
<td>.009</td>
</tr>
<tr>
<td>Within groups</td>
<td>497.345</td>
<td>85</td>
<td>5.851</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>539.377</td>
<td>86</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Differences across participants teaching the three science subjects. The normally distributed total complexity scores for the participants were used in a one-way ANOVA to examine whether the $z$-scores was a function of their teaching subjects. Homogeneity of variance was not significant, Levene’s $F(2, 84) = 2.88, p = 0.06$, indicating that the assumption underlying the application of ANOVA was met. An alpha level of 0.05 was used for subsequent analysis. The one-way ANOVA of the total complexity scores by their teaching subjects produced no statistically significant difference among the three groups ($F(2,84) = 0.82, p = 0.44$).
4.2.6 Summary of UoCS survey results

To summarize, the results from the corresponding tests for salient complex systems ideas were consistent. The teachers fared the best in the idea of decentralization with a complex level of understanding. They showed somewhat complex level of understanding in the ideas of nonlinearity and non-determinism, and emergence and self-organization. However, they generally perceived complex systems to be isolated and static events, that is, they did not see complex systems as having an open and dynamic nature.

Further analysis of the results using the demographic information revealed three additional findings. First, there was no clustering effect of the responses, that is to say, there was no indication that differences in the teachers’ complex systems understanding were due to the schools they were teaching in. Second, teachers who had prior awareness of complex systems were noted to have a significantly greater complex systems understanding compared to teachers without such prior awareness. Third, there was no statistically significant difference in their complex systems understanding – based on the means of total complexity scores – between the three groups of subject teachers.

4.3 RQ 1b: Are there complex systems ideas that are more difficult than others for these teachers to understand, and if so, what are these?

Two sets of results informed this RQ. It was found that the idea of decentralization is generally better understood by the teachers compared to ideas of nonlinearity and non-determinism, and emergence and self-organization. The ideas of open and dynamic nature were least understood by the teachers.
4.3.1 Ecology question

The teacher scores in each category of complex systems ideas to the open-ended ecology question are summarized in Table 16. The simple frequency count showed that for the ideas of nonlinearity and non-determinism, half of the responses were at a level 2 (somewhat complex) understanding; and for open and dynamic nature, most responses were at either level 1 (clockwork) or level 2 understanding. These two categories of ideas appeared to be more challenging for the teachers to express in the context of this ecology question than the other two categories. Almost two-thirds of the responses were at level 2 understanding for emergence and self-organization, and more than half of the participants appeared to have a complex understanding for decentralization.

Table 16

Breakdown of scoring for each category of complex systems ideas

<table>
<thead>
<tr>
<th>Category</th>
<th>Level 1 (Clockwork)</th>
<th>Level 2 (Somewhat complex)</th>
<th>Level 3 (Complex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinearity and non-determinism</td>
<td>20</td>
<td>44</td>
<td>25</td>
</tr>
<tr>
<td>Open and dynamic nature</td>
<td>40</td>
<td>40</td>
<td>9</td>
</tr>
<tr>
<td>Emergence and self-organization</td>
<td>9</td>
<td>57</td>
<td>23</td>
</tr>
<tr>
<td>Decentralization</td>
<td>11</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>Total:</td>
<td>80 (22%)</td>
<td>171 (48%)</td>
<td>105 (30%)</td>
</tr>
</tbody>
</table>

The Generalized Partial Credit Model (GPCM: Muraki, 1992) was next applied to analyze the relative difficulties in articulating the categories of various ideas. To evaluate the item difficulty of the four items, the GPCM was run on IRTPRO estimation engine (version 4.54). The model converged satisfactorily at critical value = 0.005, and had no items fit statistical significance. This indicated a good model fit. The categories were also found to be reliable in measuring the teachers’ understanding of complex systems ideas.
(composite reliability = 0.69). All four categories could also distinguish them based on their abilities, as their discrimination parameters ranged from 0.82 to 1.86. This meant that the question was suitable for measuring the categories theorized. Table 17 presents the four categories of complex systems ideas, their difficulty parameters, and their discrimination parameters. As indicated by the difficulty parameters, open and dynamic nature ideas were found to be most difficult among these teachers; nonlinearity and non-determinism ideas were found to be at the intermediate level; and emergence and self-organization, and decentralization ideas were the least difficult.

Table 17

Parameter estimation of the categories of complex systems ideas

<table>
<thead>
<tr>
<th>Categories</th>
<th>Difficulty parameter (SE)</th>
<th>Slope (SE)</th>
<th>Maximum Item Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinearity and non-determinism</td>
<td>-0.11 (0.16)</td>
<td>1.86 (0.95)</td>
<td>1.05</td>
</tr>
<tr>
<td>Open and dynamic nature</td>
<td>0.82 (0.29)</td>
<td>1.51 (0.84)</td>
<td>0.75</td>
</tr>
<tr>
<td>Emergence and self-organization</td>
<td>-0.68 (0.39)</td>
<td>0.82 (0.40)</td>
<td>0.19</td>
</tr>
<tr>
<td>Decentralization</td>
<td>-0.90 (0.25)</td>
<td>1.35 (0.50)</td>
<td>0.84</td>
</tr>
</tbody>
</table>

N = 89

4.3.2 Part A of Perception questionnaire

In Part A of the Perception questionnaire, teachers were asked to rank in order of their perceived difficulty (from 1 least difficult to 4 most difficult) in understanding the complex systems ideas. Mean and mode scores for each category of ideas provided a relative ranking of their difficulty from the teachers’ perceptions (see Table 18). The idea of decentralization was deemed the easiest to understand, followed by those of emergence and self-organization, and nonlinearity and non-determinism. Ideas of open and dynamic nature were ranked to be the most difficult to understand.
Table 18

Means, modes and standard deviations of participants’ perceived difficulty of ideas

<table>
<thead>
<tr>
<th>Complex systems ideas</th>
<th>Mean score (SD)</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decentralization</td>
<td>1.77 (0.9)</td>
<td>1</td>
</tr>
<tr>
<td>Emergence and self-organization</td>
<td>2.62 (1.11)</td>
<td>3</td>
</tr>
<tr>
<td>Nonlinearity and non-determinism</td>
<td>2.62 (1.12)</td>
<td>3</td>
</tr>
<tr>
<td>Open and dynamic nature</td>
<td>2.99 (0.99)</td>
<td>4</td>
</tr>
</tbody>
</table>

4.3.3 Summary of ecology question and Part A of Perception survey results

The two sets of findings converged well. From the GPCM analysis, decentralization was the least difficult idea to understand, followed by emergence and self-organization, and nonlinearity and non-determinism. The ideas of open and dynamic nature were the most difficult to articulate. From the teachers’ self-reported ranking of these ideas, ideas of open and dynamic nature were the most difficult to understand while decentralization was the easiest.

4.4 RQ 2a: To what extent complex systems ideas are conveyed during science teachers’ instructional practices?

The RQ is answered from the statistical analyses of the responses to Part B of the Perception questionnaire and the coding of the teaching episodes. This provides an overall picture of as well as insights into the instructional practices. Generally, the findings indicated that complex systems ideas were conveyed in Grades 11 and 12 science lessons. The teachers surveyed were able to cite wide-ranging topics where they perceived complex systems ideas were taught. Complex systems ideas were also conveyed in the science lessons of the six science teachers. However, what ideas and how explicit they were conveyed varied among teachers.
4.4.1 Part B of Perception questionnaire

In Part B of the Perception questionnaire, the participants were asked to reflect on their teaching in the past six months to describe what and how complex systems ideas have been incorporated in their lessons. 49% of the teachers \( N = 84 \) indicated that they conveyed complex systems ideas in their lessons. A breakdown by subjects showed that a greater proportion of biology \( (67\%) \) teachers perceived that they incorporated these ideas into their lessons compared to chemistry \( (52\%) \) and physics teachers \( (30\%) \). Table 19 shows the proportion by subjects.

Table 19
Proportion of teachers who indicated incorporating complex systems ideas in lessons

<table>
<thead>
<tr>
<th></th>
<th>Biology</th>
<th>Chemistry</th>
<th>Physics</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>7 (33%)</td>
<td>16 (48%)</td>
<td>21 (70%)</td>
<td>44 (51%)</td>
</tr>
<tr>
<td>Yes</td>
<td>14 (67%)</td>
<td>17 (52%)</td>
<td>9 (30%)</td>
<td>40 (49%)</td>
</tr>
<tr>
<td>Total</td>
<td>21 (100%)</td>
<td>33 (100%)</td>
<td>30 (100%)</td>
<td>84 (100%)</td>
</tr>
</tbody>
</table>

The 40 science teachers who responded affirmatively stated a wide range of topics and scientific concepts in the ‘A’ level science syllabi where they thought the ideas were incorporated in their instructional practices. Several teachers suggested more than one topic. This finding implied that these teachers were able to perceive how complex systems ideas have been conveyed in their regular science instruction. Table 20 tabulates these topics. Incidentally, the topics selected for video recording were among the topics mentioned too.
Table 20

*Topics mentioned by teachers where they thought they incorporated complex systems ideas*

<table>
<thead>
<tr>
<th>Topics in 'A' Level Syllabi</th>
<th>Number of times cited/implied</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biology topics</strong></td>
<td></td>
</tr>
<tr>
<td>Genetic Basis for Variation</td>
<td>3</td>
</tr>
<tr>
<td>DNA and Genomics</td>
<td>3</td>
</tr>
<tr>
<td>Cellular Functions</td>
<td>3</td>
</tr>
<tr>
<td>Cellular Physiology and Biochemistry</td>
<td>4</td>
</tr>
<tr>
<td>Diversity and Evolution</td>
<td>8</td>
</tr>
<tr>
<td><strong>Chemistry topics</strong></td>
<td></td>
</tr>
<tr>
<td>Atoms, Molecules and Stoichiometry</td>
<td>2</td>
</tr>
<tr>
<td>Chemical Bonding</td>
<td>2</td>
</tr>
<tr>
<td>Chemical Energetics</td>
<td>2</td>
</tr>
<tr>
<td>Equilibria</td>
<td>3</td>
</tr>
<tr>
<td>Organic Chemistry</td>
<td>4</td>
</tr>
<tr>
<td>The Gaseous State</td>
<td>6</td>
</tr>
<tr>
<td><strong>Physics topics</strong></td>
<td></td>
</tr>
<tr>
<td>Quantum Physics</td>
<td>1</td>
</tr>
<tr>
<td>Electricity</td>
<td>1</td>
</tr>
<tr>
<td>Work, Energy, Power</td>
<td>2</td>
</tr>
<tr>
<td>Forces</td>
<td>2</td>
</tr>
<tr>
<td>Electromagnetic Induction</td>
<td>2</td>
</tr>
<tr>
<td>Thermal Physics</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>

4.4.2 Video transcripts

Recall that video transcripts were analyzed to determine the extent – what and how explicit – complex systems ideas were translated in the six teachers’ instructional practice. There were 240 teaching episodes in all, ranging between 5 and 25 minutes in length each. The number of teaching episodes coded varied slightly between 37 (Bill and Johnny) and 45 (Elly), with an average of 40 episodes per teacher. Of these 240 episodes, 183 (or 76% of total episodes) contained evidence of at least one complex systems idea being implicitly conveyed or explicitly taught. This was anticipated as the lessons recorded (i.e., evolution, cellular structure and functions, organic chemistry, kinetic...
theory of matter, electricity, and work, energy and power) were supposed to cover scientific concepts related to complex systems ideas.

A breakdown of these episodes (see Table 21) by teachers revealed that two biology teachers generally incorporated complex systems ideas into their lessons more often than their chemistry and physics counterparts. On average, the two biology teachers were coded to teach complex systems ideas explicitly or referred to such notions implicitly in 88% of the episodes, compared to 79% for the chemistry teachers and 66% for the physics teachers.

Table 21

Breakdown of teaching episodes

<table>
<thead>
<tr>
<th>Subject</th>
<th>Biology</th>
<th>Chemistry</th>
<th>Physics</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elly</td>
<td>Jeremy</td>
<td>Bill</td>
<td>Willie</td>
</tr>
<tr>
<td>Teacher</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of teaching episodes</td>
<td>45</td>
<td>40</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>Episodes with at least one complex systems idea implicitly or explicitly conveyed</td>
<td>38 (84%)</td>
<td>37 (93%)</td>
<td>28 (76%)</td>
<td>31 (82%)</td>
</tr>
<tr>
<td>88%</td>
<td>79%</td>
<td>66%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Illustrated in Table 22 is the breakdown of scoring for the video transcripts using the CSICM-B. Recall the aim of coding the transcripts using the CSICM-B was to determine the extent (i.e., what and how explicit) the various complex systems ideas were conveyed. It did not attempt to ascertain the level of complexity of each idea contained within an episode. Overall, the ideas of nonlinearity and non-determinism, and open and dynamic nature were largely not conveyed in the science classrooms of the six teachers (mean score, MS < 0.66), while those of decentralization, emergence and self-
organization were either implicitly conveyed or only explicitly taught at times (0.66 < MS < 1.33). However, at individual teacher level, the extent the various ideas were translated in instructional practices was uneven.

Table 22

**Breakdown of scoring for complex systems ideas**

<table>
<thead>
<tr>
<th>Teacher Coding</th>
<th>Elly</th>
<th>Jeremy</th>
<th>Biology</th>
<th>Bill</th>
<th>Willie</th>
<th>Chemistry</th>
<th>Casey</th>
<th>Johnny</th>
<th>Physics</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nonlinearity and non-determinism</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 0</td>
<td>20</td>
<td>37</td>
<td>67%</td>
<td>28</td>
<td>27</td>
<td>73%</td>
<td>35</td>
<td>30</td>
<td>86%</td>
<td>74%</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
<td>67%</td>
<td>28</td>
<td>27</td>
<td>73%</td>
<td>35</td>
<td>30</td>
<td>86%</td>
<td>74%</td>
<td></td>
</tr>
<tr>
<td>Level 1</td>
<td>6</td>
<td>3</td>
<td>11%</td>
<td>4</td>
<td>0</td>
<td>5%</td>
<td>4</td>
<td>6</td>
<td>13%</td>
<td>10%</td>
</tr>
<tr>
<td>Level 2</td>
<td>19</td>
<td>42%</td>
<td>22%</td>
<td>5</td>
<td>11</td>
<td>22%</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td>3%</td>
</tr>
<tr>
<td>Mean score</td>
<td>0.97</td>
<td>0.08</td>
<td>0.39</td>
<td>0.58</td>
<td>0.27</td>
<td>0.22</td>
<td>0.42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Open and dynamic nature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 0</td>
<td>17</td>
<td>20</td>
<td>38%</td>
<td>29</td>
<td>15</td>
<td>11%</td>
<td>20</td>
<td>54</td>
<td>72%</td>
<td>81%</td>
</tr>
<tr>
<td>Level 1</td>
<td>5</td>
<td>8</td>
<td>11%</td>
<td>4</td>
<td>16</td>
<td>13%</td>
<td>6</td>
<td>14</td>
<td>14%</td>
<td>9%</td>
</tr>
<tr>
<td>Level 2</td>
<td>23</td>
<td>27%</td>
<td>40%</td>
<td>4</td>
<td>11</td>
<td>15%</td>
<td>5</td>
<td>12</td>
<td>19%</td>
<td>16%</td>
</tr>
<tr>
<td>Mean score</td>
<td>1.13</td>
<td>0.74</td>
<td>0.33</td>
<td>0.53</td>
<td>0.38</td>
<td>0.41</td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Emergence and self-organization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 0</td>
<td>11</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>20</td>
<td>54%</td>
<td>10</td>
<td>40%</td>
<td>21</td>
<td>63%</td>
</tr>
<tr>
<td>Level 1</td>
<td>5</td>
<td>4</td>
<td>4%</td>
<td>12</td>
<td>32%</td>
<td>17</td>
<td>15</td>
<td>35%</td>
<td>8</td>
<td>28%</td>
</tr>
<tr>
<td>Level 2</td>
<td>29</td>
<td>26</td>
<td>64%</td>
<td>5</td>
<td>14</td>
<td>21%</td>
<td>7</td>
<td>16</td>
<td>0</td>
<td>9%</td>
</tr>
<tr>
<td>Mean score</td>
<td>1.39</td>
<td>1.40</td>
<td>0.60</td>
<td>1.03</td>
<td>0.67</td>
<td>0.22</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Decentralization</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 0</td>
<td>22</td>
<td>49%</td>
<td>10%</td>
<td>31%</td>
<td>22</td>
<td>59%</td>
<td>14</td>
<td>52%</td>
<td>20</td>
<td>59%</td>
</tr>
<tr>
<td>Level 1</td>
<td>1</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>7</td>
<td>9</td>
<td>21%</td>
<td>8</td>
<td>19%</td>
<td>20%</td>
</tr>
<tr>
<td>Level 2</td>
<td>22</td>
<td>35</td>
<td>49%</td>
<td>8</td>
<td>22%</td>
<td>15</td>
<td>27%</td>
<td>15</td>
<td>35%</td>
<td>21%</td>
</tr>
<tr>
<td>Mean score</td>
<td>1.00</td>
<td>1.78</td>
<td>0.63</td>
<td>1.02</td>
<td>0.89</td>
<td>0.32</td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: percentages reflect the relative proportion the levels were coded for each category of ideas.*
**Elly, biology teacher.** Elly was teaching Diversity and Evolution at the time of study. She incorporated complex systems ideas in 84% of her episodes. The ideas of emergence and self-organization (MS = 1.39) were often explicitly taught with 64% of her episodes coded “Level 2” for these ideas. The other sets of ideas were only taught explicitly at times or largely conveyed implicitly (0.97 < MS < 1.13). Instances where complex systems ideas were conveyed included instruction involving the concepts of natural selection and selection pressures over extended time for evolution and speciation to occur, and neutral theory where evolution is believed to be a random process.

**Jeremy, biology teacher.** Jeremy was teaching the topics of Cellular Function, and DNA and Genomics. Compared to Elly, Jeremy also incorporated complex systems ideas frequently in 93% of his episodes. However, not all ideas were conveyed to a similar extent. On the one hand, decentralization, and emergence, and self-organization were often translated in his practice as he explicitly taught these ideas (MS = 1.78 and 1.40 respectively) in more than two-thirds of the episodes. On the other hand, the ideas of open and dynamic nature (MS = 0.74) were only explicitly taught in 27% of the episodes, while nonlinearity and non-determinism (MS = 0.08) were seldom conveyed at all. Instances where complex systems ideas were conveyed included instruction of how cellular organelles and membranes form from the self-orienting behavior of the phospholipids, how their functions arise from these structures, and how DNA molecules are replicated semi-conservatively.

**Bill, chemistry teacher.** Bill was teaching Organic Chemistry at the time of study. He incorporated complex systems ideas in 76% of the episodes. However, based on the
interpretation of the mean scores, the ideas were largely not taught explicitly (MS < 0.66). In particular, there was few mentions or suggestions of the ideas of nonlinearity and non-determinism, and open and dynamic nature (MS = 0.39 and 0.33 respectively). Ideas of emergence and self-organization, and decentralization fared slightly better (MS = 0.59 and 0.46 respectively). Instances where complex systems ideas were conveyed included instruction of free radical substitution mechanism, product chirality (i.e., mirror images but not superimposable) arising from reaction mechanisms, and various factors determining the type of nucleophilic substitution reactions.

**Willie, chemistry teacher.** Willie was teaching Kinetic Particle Theory at the time of study. He incorporated complex systems ideas in 82% of the episodes. Not all ideas were conveyed to a similar extent. On the one hand, emergence and self-organization, and decentralization were explicitly taught or hinted in more than 60% of the episodes (MS = 0.67 and 0.89 respectively). On the other hand, the ideas of nonlinearity and non-determinism, and open and dynamic nature were largely not conveyed (MS = 0.58 and 0.53 respectively). Instances where complex systems ideas were conveyed included instruction of the random particulate movement that arises from multiple collisions and diffusion as process that involves continual movement of molecules over time.

**Casey, physics teacher.** Casey was teaching Electricity and Electromagnetism at the time of study. She conveyed complex systems ideas in 79% of her episodes. Similar to Willie’s episodes, the ideas of emergence and self-organization, and decentralization (MS = 0.67 and 0.89 respectively) were more often explicitly taught or hinted than the other ideas. The ideas of nonlinearity and non-determinism, and open and dynamic nature were
less prevalently not taught ($MS = 0.27$ and $0.38$ respectively). Instances where complex systems ideas were conveyed included instruction of how the external environmental conditions affect various electrical components such as light-dependent resistors and thermistors, how the various components change the current and potential differences in electrical circuits, and how Lorentz force is induced as a result of the interaction between the electromagnetic fields.

*Johnny, physics teacher.* Johnny was teaching Work, Energy and Power at the time of study. He conveyed complex systems ideas in $76\%$ of the episodes. Johnny generally did not introduce or allude to the ideas ($MS$s between $0.22$ and $0.41$). The few instances where complex systems ideas were conveyed included instruction of non-uniform forces in extended springs and in deformed materials, various energy considerations in systems, dissipative systems subjected to energy losses and gains.

**4.4.3 Summary of Part B of Perception survey results and video transcripts analysis**

Generally, complex systems ideas were conveyed in Grades 11 and 12 science lessons. The teachers surveyed were able to cite wide-ranging topics where they perceived complex systems ideas were taught. However, from the coding of the video transcripts of their instructional practices, the extent the ideas were incorporated in the lessons varied. There were two broad findings.

The first finding concerned the incorporation of complex systems ideas in the different subjects. Biology teachers appeared to teach these ideas more often than chemistry and physics teachers. From the Perception survey, more than two-thirds of the biology teachers said that these ideas were communicated in their practices. In
comparison, slightly less than a third of the physics teachers and half of the chemistry teachers surveyed mentioned that complex systems ideas were conveyed in their lessons. The analyses of the video transcripts also suggested that the physics and chemistry teachers did not incorporate these ideas into their practices as prevalently and as explicitly as the biology teachers.

The second set concerns the variation in what ideas were taught and how explicit the ideas were conveyed at the individual teacher level. Of the four categories of ideas, decentralization, and emergence and self-organization seemed to be most prevalently conveyed in science teachers’ instructional practice (MS = 0.94 and 0.91 respectively). On the other end of the spectrum, the ideas of nonlinearity and non-determinism, and open and dynamic nature (MS = 0.42 and 0.60 respectively) appeared to be less conveyed. While there could be numerous factors contributing to this variation – including the topics being taught, the profile of the students, among others – one particular factor related to their complex systems understanding was examined. The relationship between their complex systems understanding and their instructional practices was investigated (i.e., RQ 2b) and the findings are reported in the next section.

4.5 RQ 2b: What is the relationship between science teachers’ understanding of complex systems and their instructional practices?

This RQ is answered from two levels of analyses. The first level relied on the survey responses where the results of the ecology question in the UoCS survey were associated with those of the Part B in the Perception survey. The second level examined the six teachers’ responses to the tests of complex systems understanding in the UoCS
questionnaires against their individual instructional practices. In combination, these two levels of analyses would provide both a broad picture and an in-depth insight of the possible relationship between teachers’ complex systems understanding and their instructional practice. Briefly, the findings strongly showed that science teachers with a better understanding of complex systems were more likely to incorporate these ideas into their instructional practices and teach them explicitly.

4.5.1 Association between results of ecology question and Part B of Perception survey

A chi-square test of independence was performed to examine the association between science teachers’ complex systems understanding and their indications of incorporating complex systems ideas in their instructional practices. Table 23 presents the contingency table. In all, there were 84 valid pairs of responses. 13% of the teachers with a clockwork perception of complex systems indicated that they incorporated complex systems ideas into their instructional practices, while 73% of those with a complex perception indicated likewise. For those with a somewhat complex perception, about half indicated that they conveyed the ideas in their lessons. The relation between these variables was significant, $X^2 (2, N = 84) = 13.52$, $p = 0.01$, Cramer’s $V = 0.40$, suggesting a strong association. The null hypothesis that the variables were independent was rejected. In short, teachers with a better understanding of complex systems ideas were more likely to indicate that they incorporated these ideas into their practices.
Table 23

Contingency table of complex systems understanding and indication of incorporating complex systems ideas into instructional practices

<table>
<thead>
<tr>
<th>Classification of total complexity score</th>
<th>Indication of incorporating complex systems ideas into instructional practices</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 (No)</td>
<td>1 (Yes)</td>
</tr>
<tr>
<td>1 (Clockwork)</td>
<td>13 (87%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>2 (Somewhat complex)</td>
<td>25 (54%)</td>
<td>21 (46%)</td>
</tr>
<tr>
<td>3 (Complex)</td>
<td>6 (27%)</td>
<td>17 (73%)</td>
</tr>
<tr>
<td>Total</td>
<td>44 (52%)</td>
<td>40 (48%)</td>
</tr>
</tbody>
</table>

Note. Parentheses indicate the percentage of total count

4.5.2 Comparison between ecology question results and video transcripts analysis

The scores to each of the six teachers’ tests of complex systems understanding and the analyses of their instructional practices were examined to provide a sense of his or her state of understanding and practice of each set of ideas. The two sets of results were then compared to determine the relationship between complex systems understanding and practice. A narrative was written to illustrate the relationship.

Recall that there were three tests of complex systems understanding in all; two for each set of ideas (see sections 3.5.1.2 and 3.6.1). These three tests were the visualization exercise that assessed participants’ perception of emergence and self-organization, and decentralization, the causal mapping exercise that assessed their understanding of nonlinearity and non-determinism, and open and dynamic nature, and the ecology question that tested their comprehension of the four sets of ideas. In addition, to determine the extent the various complex systems ideas were conveyed in the teachers’ lessons, their instructional practices were coded using the CSICM-B.
Table 24 illustrates the various scores the six teachers received in the various tests of complex systems understanding and the extent these teachers conveyed complex systems ideas into their instructional practice. It appeared that, in general, the more complex an understanding of an idea, the more explicit the idea would be conveyed in the lessons. Elly’s and Johnny’s cases were used to illustrate the relationship between complex systems understanding and practice. Elly represented a teacher with good understanding of complex systems ideas and was seen conveying these ideas in her practice. Johnny exemplified a teacher on the other end of the spectrum with a less-than-complex understanding and did not often convey these ideas in his lessons. However, there were anomalies to this generalized relationship; instances from the other teachers illustrated some of these anomalies.

Table 24

Scores obtained by six teachers in various tests of complex systems understanding

<table>
<thead>
<tr>
<th>Ideas</th>
<th>Test</th>
<th>Elly</th>
<th>Jeremy</th>
<th>Bill</th>
<th>Willie</th>
<th>Casey</th>
<th>Johnny</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinearity and non-determinism</td>
<td>Web-like Causality Index scores</td>
<td>0.80</td>
<td>0.14</td>
<td>0.25</td>
<td>0.33</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>CSICM score</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CSICM-B mean score</td>
<td>0.97</td>
<td>0.08</td>
<td>0.39</td>
<td>0.58</td>
<td>0.27</td>
<td>0.22</td>
</tr>
<tr>
<td>Open and dynamic nature</td>
<td>Number of feedback loops</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>CSICM score</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>CSICM-B mean score</td>
<td>1.13</td>
<td>0.74</td>
<td>0.33</td>
<td>0.53</td>
<td>0.38</td>
<td>0.41</td>
</tr>
<tr>
<td>Emergence and self-organization</td>
<td>Proportion of statements with complex beliefs selected</td>
<td>0.80</td>
<td>0.67</td>
<td>0.50</td>
<td>0.67</td>
<td>0.67</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>CSICM score</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CSICM-B mean score</td>
<td>1.39</td>
<td>1.40</td>
<td>0.60</td>
<td>1.03</td>
<td>0.67</td>
<td>0.22</td>
</tr>
<tr>
<td>Decentralization</td>
<td>Decentralized model selected</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>CSICM score</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CSICM-B mean score</td>
<td>1.00</td>
<td>1.78</td>
<td>0.63</td>
<td>1.02</td>
<td>0.89</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Elly possessed perhaps the best understanding of complex systems ideas among the teachers based on her scores in the three tests. Figures 29 and 30 show Elly’s complex causal map and response to the ecology question which give a sense of her deep understanding in complex systems. In her causal map, not only were there six feedback loops (i.e., a complex understanding of open and dynamic nature), but also the Web-like Causality Index score was 0.8 (i.e., a nonlinear and non-deterministic perception). 80% of the statements she chose described the bird flocking phenomenon as emergent and self-organized in nature (i.e, a complex understanding of these ideas) and she also selected the decentralized model of ant foraging behaviors. In the ecology question, she displayed a Level 3 (i.e., complex) understanding in all four categories of complex systems ideas.
Figure 29. Elly’s causal map
Figure 30. Elly’s response to ecology question

In terms of her instructional practices, Elly conveyed complex systems ideas to a large extent. Ideas of emergence and self-organization were explicitly taught in numerous occasions. Although the other three categories of complex systems ideas were coded as somewhat taught explicitly or largely conveyed implicitly, the CSICM-B scores for these ideas were comparable or higher than those of other five teachers. To give an illustration of how Elly’s instructional practices incorporated some of these ideas, an excerpt of her explanation of a problem on differential selection pressure was used.

Elly We are looking at the frequency of recessive alleles influenced by selection pressure.
Which [option] shows the conditions in which recessive alleles are retained in a population? I want you to think about small-scale factors and large-scale factors that may account for the retention of recessive alleles... [murmurs of ‘environmental variation’ heard] Can environmental changes select for recessive alleles? There is a possibility that might favor the extreme phenotypes. The two ends, or one end or the other. Both ends of the bell curve. So this is the case where you see your recessive alleles being retained. Another reason of how you retain your recessive alleles is by the heterozygote advantage. There are benefits of being a heterozygote like immunity to diseases or better food absorption and so on. Another reason is also the lack of selection advantage, that means all types of alleles have equal chance of being passed down to the offspring. That would also help the recessive alleles in the population. And the last one, polymorphism. Why is that when you have many phenotypes, it might help retain the recessive alleles? It simply means that there is a higher chance of certain phenotypes selected for and others selected against. There are many variations, so this will increase the chance. So there are really a number of possible conditions or factors contributing to the retention.

In this excerpt, it could be seen that the idea of decentralization was brought up through the elaborate illustration of various factors affecting the retention of recessive alleles in a population; the idea of non-determinism was highlighted when Elly talked about “chance” and “possibility” of retention; and the idea of emergence was implied when she asked the students to think about component- and system-level (i.e., “small” and “large”-scale) factors giving rise to the phenomenon. Furthermore, as mentioned in section 4.4.2, as many as 84% of Elly’s episodes conveyed complex systems ideas.

While Elly demonstrated the case of a science teacher having a complex understanding of the ideas and demonstrating complex systems instruction in her practices to a large extent, Johnny represented a teacher on the other end of the spectrum. Johnny had the least complex understanding of the ideas based on his scores in the three tests. Figures 31 and 32 show Johnny’s causal map and response to the ecology question which give a sense of his understanding. He constructed a causal map with no feedback loops and a low Web-like Casualty Index score, which inferred a linear and deterministic, and static and isolated interpretation of the socio-scientific issue. He also
selected statements that showed his non-emergent, intentional and centralized belief of the ant foraging behavior. He scored mostly a Level 1 (clockwork perception) on the ideas of complex systems in the ecology question as he did not perceive that the geese would “affect the system.” This is despite sufficient time and encouragement was given for him to write more.

Figure 31. Johnny’s causal map

   - The system
   - Initially will not affect because there’s only so geese & the geese’s birth & non-biotic elements are big/large enough to accommodate.
   - Outlining when the geese multiply the number, the ecological systems will remain

Figure 32. Johnny’s response to ecology question

In terms of his instructional practices, Johnny was seen to convey these ideas only sporadically. Most of the ideas were largely not conveyed with the exception of open and dynamic nature where more than half of episodes were coded as conveying these ideas
implicitly or explicitly. Even in the teaching of concepts where complex systems ideas could be incorporated, Johnny did not do so. Take for instance an episode when Johnny was teaching about the derivation of the formula for elastic potential energy of a spring obeying Hooke’s Law.

Johnny \textit{How do we derive this? Consider a spring [which] obeys Hooke’s Law. So you get a force-extension graph like this. A straight line that passes through the origin. The work done by force } F \textit{extends the spring by a little } dx \textit{. So the work done will be called } dW \textit{. } dW \textit{is actually the amount of force times the little extension. And we can replace the force with } kx \textit{ because the spring is obeying Hooke’s Law. So you can write } dW = kx \, dx \textit{. If you want to know the total work done, when you stretch the spring from zero extension to } x \textit{, you integrate } kx \textit{ with respect to } x \textit{. You get } \frac{1}{2} kx^2 \textit{.}

Notice that this formula for the elastic potential energy of a spring showed a function of the square of spring extension. In other words, the relationship is not a linear one. However, Johnny did not proceed to explain about the nature of this relationship, which could convey the idea of nonlinearity. In subsequent episodes, there was no further explanation of this relationship either.

The two case examples illustrated that generally, when a science teacher had a better understanding of complex systems, there was more frequent and explicit teaching of complex systems ideas. Conversely, when a science teacher had a poor understanding of complex systems, the ideas were less conveyed. However, as in any qualitative data analysis, it is also necessary to point out any anomalous instances to this general relationship. For instance, Jeremy did not demonstrate a complex understanding of open and dynamic nature; he featured one feedback loop in his causal map and his response to the ecology question presented an isolated and static perception. Despite this poor understanding of open and dynamic nature, analysis of his episodes revealed these ideas were conveyed explicitly at times. Bill on the other hand, demonstrated a complex
understanding of emergence and self-organization. Yet analysis of his episodes showed that these ideas were largely not conveyed in his lessons. Although these anomalous instances were rare, it indicated the possibility that there might be other factors influencing instructional practices of complex systems ideas.

4.5.3 Summary of association between ecology question and Part B of Perception results, and comparison between ecology question results and video transcripts analysis

Findings from the large-scale survey responses converged with those from the video transcripts, suggesting that there is a relationship between science teachers’ complex systems understanding and their instructional practices of complex systems ideas. A chi-square test of independence of the survey results indicated that a positive, strong and significant association between science teachers’ complex systems understanding and their indications of incorporating complex systems ideas in their instructional practices. Comparison of the six teachers’ test scores in their understanding of complex systems and their instructional practices hinted that teaching of complex systems ideas in their lessons were somewhat affected by what they know about these ideas. There were few instances that pointed to the contrary, indicating the possibility of other factors influencing instructional practices. What these factors might be were explored in RQ 3.
4.6 RQ 3: What are the teachers’ reasons behind the perceived difficulties in understanding and teaching these complex systems ideas?

Finding out why science teachers may (or may not) find difficulty in understanding and teaching complex systems ideas can help clarify the challenges and issues that may need addressing in future efforts to improve the learning and instruction of complex systems. RQ 3 is answered from the analyses of the responses to Part C of the Perception questionnaire and the interview transcripts of the six teachers. The survey findings revealed that more than half of the science teachers found challenging in understanding complex systems ideas. They attributed the difficulty to the unfamiliarity with this lens of interpreting scientific systems and phenomena, and they felt that this understanding would improve if they were given more exposure, learning opportunities and information regarding complex systems ideas. The responses from interviewed teachers generated three themes on why they felt that the complex systems ideas were difficult to understand and teach. These included unfamiliarity with the complexity lens, the difficulty in visualizing underlying mechanisms, and the lack of complex systems emphasis in the current curriculum and assessment. The following sections describe these findings.

4.6.1 Part C of Perception questionnaire

In Part C of the Perception questionnaire, the participants were asked if they found complex systems ideas challenging to understand and why. They were given a list of twelve statements to choose from, and they could pick as many reasons as they deemed fit. There was also an option for them to fill in other reasons not listed. The reasons in this list were abstracted from what the literature suggests about possible causes for
difficulties in understanding complex systems, and further brainstormed and piloted to develop the item statements (see section 3.5.2). As explained in section 3.6.5, factor analysis could not be performed on the reasons due to the small sample size; descriptive statistics were used to provide insight on the selected reasons.

56% (or 48) of the science teachers found complex systems ideas difficult to understand. Table 25 illustrates the percentage agreement with each statement item; only items agreed by more than 10% of the respondents were reported. Many of the teachers opined that the greatest impediment to understanding complex systems ideas might be those related to the learning of these ideas. As many as 41% of the 48 teachers agreed that they required more experience with models depicting complex systems so as to get a better understanding. While 35% would like additional information about the ideas, 30% of the teachers agreed that they required more learning opportunities that convey these ideas. A smaller proportion viewed that it was due to the nature of complex systems that made these ideas difficult to comprehend: 18% felt that a fundamental shift would be necessary in how they view scientific phenomena; 17% acknowledged that they had trouble interpreting scientific phenomena from the complex systems perspective; and 13% believed that more time would be required to change their perception of scientific systems. Interestingly, none of the teachers selected reasons that are related to their disbelief in this perspective.
Table 25

*Percentage agreement (>10%) on reasons for difficulty in understanding complex systems*

<table>
<thead>
<tr>
<th>Why do you find complex systems ideas difficult to understand? (N = 48)</th>
<th>Percentage agreement (i.e., those reasons that were selected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I need to learn about these ideas by experiencing with models depicting complex systems.</td>
<td>41%</td>
</tr>
<tr>
<td>I need additional information about these ideas.</td>
<td>35%</td>
</tr>
<tr>
<td>I require more learning opportunities that convey these ideas.</td>
<td>30%</td>
</tr>
<tr>
<td>Understanding the ideas require a fundamental shift in how I view scientific phenomena.</td>
<td>18%</td>
</tr>
<tr>
<td>I have trouble perceiving most scientific phenomena with these ideas.</td>
<td>17%</td>
</tr>
<tr>
<td>It will take time to change my perception of complex systems.</td>
<td>13%</td>
</tr>
</tbody>
</table>

In sum, these results showed that complex systems ideas were perceived to be difficult to understand by half of the science teachers surveyed. This difficulty appeared to be due to their lack of exposure to these ideas through learning opportunities and models which may in turn give rise to their struggle in interpreting scientific systems and phenomena through this unfamiliar lens.

4.6.2 Interviews

The six teachers were interviewed after the last video recording of their lessons. Recall that the purpose of the interviews was to find out the reasons for the difficulties these teachers might face in understanding and teaching complex systems ideas. Generally, the six teachers did not foresee or face any difficulty in understanding these ideas. This was largely because of their prior learning opportunities in complex systems. They felt that the ideas were applicable to real-life examples and were aligned to the subject disciplines they taught. However, they believed they would experience more
difficulty in teaching these ideas because their Grades 11 and 12 students were unfamiliar with complex systems ideas and the underlying ideas were not easy to visualize. They also reasoned that these ideas were not emphasized in the science syllabi, making the teaching of these ideas an instructional challenge as they were not tested in the high-stakes national assessments.

Understanding complex systems ideas. The six teachers did not perceive the complex systems ideas to be difficult to understand. Collectively, three reasons were offered on why these teachers did not feel the ideas to be a challenge.

The first reason was related to their prior exposure to complex systems. Four teachers – Elly, Jeremy, Casey and Willie – attended modules or courses related to complex systems or system thinking during their undergraduate and graduate studies. When asked to describe complex systems ideas, even though the teachers did not use standard terms to illustrate, the teachers were able to explain the essence of the ideas. For instance, as Casey recalled,

... yes I remember now that you have described. Not in those terms, no. But nonlinearity, I learn[ed] about the cascading effect of simulated emission during laser operation. That is nonlinearity right?

Elly also mentioned specifically about having learned emergence as a core idea in understanding evolution.

Emergence is something very important in understanding many biology concepts. I recall my lecturer went through why biological life is basically a result of so many little things affecting one another, like your cells, tissues, organs and giving rise to life.

In other words, these teachers had the benefit of formal learning in complex systems which might have alleviated their understanding difficulty.
The second reason was related to the teachers’ perception that complex systems ideas could easily be seen in real-life examples. While prior formal learning might prove useful in understanding complex systems for the four teachers, it might not be essential. For instance, Bill and Johnny did not have such formal learning but they indicated that they read up on the topic. From their own interpretation, they felt that complex systems ideas were not difficult to comprehend because the ideas could be linked to real-life examples. For example, Johnny said that he did not find nonlinearity idea difficult because he could relate it to a “real-life” example.

... the deformation of the body, let’s say the body is deformed visibly, then it’s quite easy to understand that the force exerted on each other is nonlinear because when the body starts to deform, it is obvious to me that the force increases as the body gets deformed more and decreases when the deformation reduces. This is real-life.

Bill also talked about complex systems ideas in general and why the ideas associated with these systems could be “commonly seen.”

I can see these ideas in the world around us. Just now in the video [the youtube video on complex systems], you can see how many of the systems are complex and quite commonly seen. In fact, you look at a school organization, a classroom of pupils, these are all complex. The teacher can set a few basic rules in the classroom like one conversation at a time, points for classroom participation, and you can see wonders in student engagement. This is emergence and self-organization, no?

The third reason was related to their perception that the subject disciplines they taught lent themselves nicely to a complex systems perspective. This helped them to understand complex systems ideas easily through their respective areas of specialization. For instance, in addition to the quote provided earlier in this section, Elly also articulated why understanding complexity is necessary for biology.

[Learning about biology] requires one to know about the inter-relationships among the various components in the system very well. We need to appreciate how these components interact with one another and often in very complicated ways, a combination of these biological interactions results in life. Life, you know, that is about as complex as you can get.
Likewise, Bill explained that many “chemical systems are complex in nature” and his familiarity with these systems made understanding complex systems easy.

... it was not difficult to fit complex systems ideas into chemical reactions. Chemical systems are complex in nature. We are not talking about one particle interacting with one particle to form a compound. We are talking about moles of, you know Avogadro’s mole concept, millions of particles hitting one another and with the right conditions and energy, form compounds.

Casey too believed that understanding the properties of systems and the behaviors of the components was crucial for learning physics.

... often [learning] physics is about learning the laws that govern the behaviors. For example, gravitation law. When you have two bodies, you can determine the motion and forces. However, when you have more planets, the system becomes more complex and calculation is less straightforward. But even with the erratic movement, you get some regularity in the orbit as a whole.

In short, these teachers felt that complex systems were not difficult to understand because of their prior formal learning opportunities, the applicability of these ideas to the real world, and the already-complex nature of the subject disciplines they taught.

Teaching complex systems ideas. While the teachers were confident with their own understanding, they were less optimistic about student learning of complex systems. Three reasons could be distilled from their interviews: students are unfamiliar with the ideas; the underlying mechanisms in complex processes are obscure; and the existing science curricula and assessments did not emphasize complex systems.

The first reason pertained to the students’ unfamiliarity with complexity in real-life situations. The teachers suggested that their students would find complex systems ideas difficult to understand because they were not used to perceiving scientific phenomena and processes from a complex systems perspective. As science teaching was often not
done from such an approach or perspective, the teachers believed that their students would not be able to situate the ideas in real-life contexts. For instance, Willie said,

*A very simple example would be the diffusion of perfume, the demonstration of diffusion [using] a purple crystal of potassium permanganate in a beaker of water. I think that’s great because that really allows students to link what they studied to the real world. But I thought most of the lessons which I went through as a student and also as a teacher, most of them tend to gloss over the connection between the physical and the molecular model world because it’s not well explicit – there is a weak link in how complex things are represented at the macro and micro levels.*

He implied that the teaching of diffusion – a complex phenomenon – often did not draw connections between the physical macroscopic world and the molecular model. This explicit connection would be necessary to teach and learn science because it would have allowed students “to link what they studied to the real world.” Other teachers added that it would be necessary to contextualize complex systems ideas in real-world scenarios so as to facilitate students’ appreciation of the ideas. For example, Elly said,

*Randomness I think that is very, it’s something that we experienced on a daily basis. So if we were to actually draw it to, I realized that when I was teaching, I try to hint them when I asked – do you think this [event] is random? So I hinted them like natural disaster, somebody just stepped on the beetle accidentally. So these are the things we experienced on a daily basis and we know that there isn’t a greater force that causes someone to step on the beetle in that sense. So I thought it’s very real-life and students understand it better. However, from my experience, they are simply not used to think this way and have a tendency to see science as pre-determined or [cast] in stone events.*

Elly believed that the idea of non-determinism or “randomness” would be less difficult to understand if it could be taught using daily experiences. However, she too acknowledged that her students’ unfamiliarity in perceiving daily or real-world situations through a complex systems lens may be the hindrance to their understanding of the ideas.

The second reason was related to the obscurity of the underlying mechanisms in complex processes. Some teachers explained that the difficulty in understanding complex systems ideas could have arisen from the challenge in visualizing component-level
behaviors and interactions which tend to be the less-visible aspects of the complex processes. For instance, Johnny placed importance in seeing deformation in action to understand nonlinearity in forces.

\[ I \text{ think the change in the force magnitude happens rapidly so it's not usually realized. If the collision or deformation occurs over a longer period of time, then it's easier to help the students understand why the force acting on the two bodies is nonlinear. So if you ask me how I [can] teach it better, I would start with something that is, maybe, I will take two objects that are more elastic, collide, and let them see the collision that takes place. During the collision, there is visible deformation, and then maybe I can put some force sensors to detect the amount of force, and that will give them a clearer and deeper understanding. } \]

In other words, he described that students typically faced difficulty in grasping the concept of this nonlinear force because of the instantaneous or ‘rapid’ change that was not easy to see. Other teachers also mentioned that being able to visualize the often-obscured mechanisms underlying the complex phenomenon was important in understanding complexity. For example, Jeremy believed picturing the membrane structure was necessary to appreciate self-organization.

\[ The \text{ membrane structure is complicated. To appreciate the ‘magic’ of biology, like how the phospholipids molecules will orientate themselves to form a bilayer, how proteins will embed themselves within this bilayer, how some substances can move in or out. These are what you call self-organization right? They have to see this structure first before they can appreciate. I have to show them how they are organized, why they are organized this way. } \]

The third reason was perhaps the most pervasive as all teachers brought this up or at least implicitly hinted at it. It was related to the lack of emphasis of these ideas in existing science syllabi. Across the three subjects, all teachers made regular references to its largely non-existent mention in the current science syllabi and commented that complex systems ideas were not tested in the national assessments. However, it is necessary to point out at this juncture that this particular reason may be contextual in
nature as Singapore’s national assessments are bounded by relatively well-defined subject syllabi. This may not necessarily be the case for other educational systems.

In biology, Elly mentioned she taught evolution as a “step-by-step linear process or flow” as opposed to a complex process because it had to do with the kind of questions the students would most likely face in national or school examinations.

I would think that it has to do with the types of questions that are being posed during exams, in their daily assignments, there is really no need for them to emphasize on the scale or emergence of it, but rather this flow, A leads to B, B leads to C, C leads to D, I would say is very fixed. They would always describe it this way, just that they might come in at different point, like they must start from B, but they will always go C, D, E, they might start from C, then D, E, so on. That’s why the emphasis on the flow.

The physics teachers also suggested that these ideas did not feature prominently in the physics syllabus and that assessing student understanding of the ideas might be difficult because of this. For example, Johnny expressed that while the idea of open nature might be important in the understanding of dissipative systems, it was not feasible to assess in the context of examination.

The biggest issue is that there could be a lot of energy input and energy output, so the question is where do they stop? Where do they draw the line? So when we give them a question, we have something in mind. We are just talking about these few phenomena, but they will be asking questions like what about heat loss to the surroundings. They will ask us questions because they understood that a system can lose energy through different ways, or gain energy from different ways but we cannot possibly account for this in our questions, so, that’s the difficulty. The exam questions are not designed this way. It would be difficult to assess what they know.

Responses along similar veins were seen from the chemistry teachers too. Willie talked about their apparent lack of mention in the syllabus. This was despite the fact that Willie designed his lesson with the ideas of nonlinearity, non-determinism and emergence in mind. Due to his belief in the importance of these ideas as a chemist, he persisted in
teaching about them. However, he also acknowledged that such instruction was not common in Grades 11 and 12 chemistry classrooms.

*The power of science is that it is predictable. But I think many people didn’t realize that at the microscopic level, particles are actually moving at a very uncertain way because there are just too many particles for us to consider. The results are not a linear consequence of [one] but many actions. Teachers do not teach this at this level because there is no need to. And most students won’t get to be exposed to this idea until much later levels in the university. Do they need it for their A levels [national examination]? No. Is it important to learn? Yes. But is it tested? No. However, I believe that it is important for them to understand the idea of random movement, nonlinearity from the very start so that they can have an idea…*

These three reasons captured how the teachers generally felt about teaching complex systems ideas in their classrooms. To address the educational problem of students’ limited awareness of complex systems, it would be prudent to take into consideration these reasons hindering complex systems instruction in any reform effort.

4.6.3 Summary of Part C of Perception results and interview analysis

To recap, it was revealed that almost half of the teachers surveyed found difficulty in understanding complex systems ideas. Many of the teachers opined that the greatest impediment to understanding complex systems ideas might be those related to the learning of these ideas. They agreed that they required more experience with models depicting complex systems, more learning opportunities that convey these ideas, and more information so as to get a better understanding. A handful of the teachers also viewed that the nature of complex systems made these ideas difficult to comprehend. They felt that more time would be required to change their perception of scientific systems and that a fundamental shift would be necessary in how they view scientific phenomena. Conversely, the six teachers interviewed did not find complex systems ideas difficult to understand. This was largely because they had prior exposure to complex
systems – through both formal and informal learning opportunities. As a result, these teachers could see the instantiation of complex systems ideas in real-life scenarios and the subject disciplines they taught.

On why the teaching of complex systems might present difficulties, the teachers interviewed pointed out that firstly, these ideas were unfamiliar to their students. Scientific phenomena and processes were often not taught from such a perspective so the students might find difficulty in contextualizing the ideas in real-world scenarios. Secondly, the teachers also suggested that the underlying mechanisms giving rise to the complexity were often obscured which can hinder instruction of these ideas. Thirdly and perhaps the most pertinent reason, appeared to be the lack of complex systems emphasis in existing syllabi and assessments. The teachers unanimously mentioned that these ideas were simply not mentioned in the science syllabi nor tested in the high-stakes assessments, and this in turn inevitably led to teachers not paying instructional attention to them.
5 DISCUSSION

5.1 Chapter Overview

In this chapter, the findings about science teachers’ understanding and teaching of complex systems and their implications are discussed. Limitations to the study are also described.

5.2 Science Teachers’ Understanding in Complex Systems

The research investigates the extent science teachers understand complex systems ideas. The argument for this research is that in order to make better sense of why students have limited awareness of complex systems, it is essential to explore the problem from the teacher perspective. Put simply, perhaps students do not know much about complex systems because teachers do not possess an adequate understanding of complex systems ideas. Prior research was done on small, selected groups of teachers and on specific ideas of complex systems; a systemic investigation of teachers’ understanding of a more comprehensive set of complex systems ideas with a more representative sample can help to better illustrate the extent of science teachers’ understanding of complex systems.

Present findings from a large sample of ninety Grades 11 and 12 science teachers in six randomly-selected schools across Singapore revealed as many as 80% of the teachers reported that they did not have prior knowledge or heard of complex systems, and teachers who possessed prior knowledge of complex systems performed significantly better on the tests of complex systems understanding than those who did not. In general, the teachers did not have a comprehensive understanding of the various complex systems
ideas. They fared the best in the idea of decentralization, possessing a complex level of perception. For non-linearity and non-determinism, and emergence and self-organization, the teachers showed a somewhat complex level of understanding. However, they tended to depict complex systems as isolated and static events or situations, and did not see these systems as open and dynamic in nature.

These present findings are consistent with those suggested in other studies. Booth-Sweeney and Sterman (2007) discovered that most of their eleven teacher-participants did not consider the various timescales over which changes may occur, and as a result, neglected their dynamic nature. Brown and Schwartz (2009) also highlighted that their teacher-participants struggled to articulate how the processes were interconnected by means of matter, even though they could affirm that the processes were connected. At the same time, these and other researchers such as Hmelo-Silver and her colleagues (2004; 2007) and Jacobson (2001) also suggested that their teacher-participants were not completely unaware of complexity; they did possess some rudimentary complex perspective. With this present research that uses a more representative sample, there is now a more conclusive awareness of the state of science teachers’ complex systems understanding.

When science teachers do not have a complete understanding of the various ideas underlying complex systems, this may pose difficulty in teaching or expressing these ideas to their students. Indeed, this research has determined this relationship which is discussed shortly in the next section 5.3. The educational problem of students’ poor understanding of complex systems may very well be related to the teachers’ incomplete
knowledge of complex systems ideas, even though this is not explored in the present study. As described in earlier chapter 1.2, current efforts in addressing the educational problem of students’ limited complex systems awareness have largely focused on promoting student learning of complex systems. This research suggests that an equal emphasis should also be placed on teachers’ professional development to ensure that the science teachers themselves know adequately about this domain.

This research also uncovers which complex systems ideas may be more difficult to understand than others for science teachers. The ordered sequence of difficulty of complex systems ideas found in the present study appears valid. Although there is no prior research performed on teachers from this angle, there are studies putting forth why certain ideas might be more difficult than others. Chi (2005) and Slotta (2011) propose that some scientific concepts and ideas may not be easier to comprehend because of the ontological categories they belong to. Chi explains that “ontological categories refer to the basic categories of realities or the kinds of existence in the world, such as concrete objects, events, and abstractions” (2005, p. 163). Emergence, self-organization, nonlinearity, non-determinism, and open and dynamic nature may represent abstractions which are ontologically more difficult. Take for instance, the ideas of open and dynamic nature – system boundaries are porous, allowing the inflow and outflow of information, matter and energy and in turn causing the system to be in a state of constant flux. These ideas require one to consider beyond the typical and observable boundaries and timescale of a system. On the other hand, decentralization is perhaps easily understood by teachers due to their more complete knowledge of the science topics they are teaching; they were
more able to visualize how the various elements of the system are connected or play a part in overall scheme of the subject. The present finding, that some ideas are more difficult than others to comprehend, will be helpful in informing professional development planners what ideas require more emphasis when designing professional development in complex systems.

5.3 Science Teachers’ Instructional Practice in Complex Systems

The present research also investigates science teachers’ instructional practices of complex systems and examines how their practices may be influenced by their complex systems understanding. From a review of the literature, it is clear that not much is known about the extent teachers teach complex systems ideas in regular science classrooms as most researchers focus on research and design of novel interventions. Additionally, the relationship between teachers’ understanding and instructional practices in this particular domain has not been established either. While this relationship is generally true in other domains of science, it is yet to be determined for the complex systems domain. Findings to RQs 2 are important because they extend the knowledge base by providing insights into the educational problem of poor students’ complex systems understanding from an instructional practice perspective.

Findings suggest that current instructional practices in conveying these ideas are not uniform. Notably, across the three science subjects, survey results and video analyses showed that biology teachers taught these ideas more often and more explicitly than chemistry and physics teachers. There was also variation in the instruction of complex systems ideas at the teacher level. Different teachers appeared to emphasize different
ideas, and how explicit the ideas were conveyed or taught also varied among the teachers. Overall, the ideas of nonlinearity and non-determinism, and open and dynamic nature were largely not conveyed in the lessons, while those of decentralization, emergence and self-organization were implicitly conveyed or only explicitly taught at times.

Noting that the investigation examines regular science instruction, the findings are not encouraging especially if understanding complex systems ideas is deemed as core in facilitating the learning of diverse scientific systems under a unifying perspective (Colella, Klopfer & Resnick, 2001; Jacobson & Wilensky, 2006; NGSS, 2013; Yoon et al., 2013). As described earlier in section 2.3.3, there have been efforts from the science education research community in the development of instructional resources, curricula and strategies aimed at facilitating the teaching of complex systems. For instance, the research project DRK12-BioGraph: Graphical Programming for Constructing Complex Systems Understanding in Biology by Massachusetts Institute of Technology and University of Pennsylvania, the series of complex systems-grounded science lessons by the NetLogo research team from Northwestern University, among others, have developed curricula that incorporate complex systems into science instruction. The present findings, however, show that regular science classrooms have yet to benefit from these commendable efforts. It is perhaps time for the science education research community to re-examine and focus on the translation and scaling up of these pieces of promising work to science classrooms all over the world.

While the differences in the instructional practices could be due to a myriad of reasons, one particular factor – teachers’ understanding of complex systems – was
examined in this study. Results from large-scale survey responses and in-depth analysis of video transcripts strongly suggest that there is a relationship between science teachers’ complex systems understanding and their instructional practices of complex systems ideas. From the surveys, a positive, strong and significant association between science teachers’ complex systems understanding and their indications of incorporating complex systems ideas in their instructional practices was obtained. Moreover, from the video analyses, teachers with a more complex understanding of certain ideas were also seen to convey those ideas in their lessons more often and more explicitly.

This finding is significant because it directly establishes the relationship between science teachers’ understanding and instructional practices in complex systems – a relationship in a subject matter domain that has yet to be explored by researchers until now. Bearing in mind that most science teachers do not have prior awareness of complex systems nor comprehensive understanding of the various ideas, this particular finding also implies that professional development to deepen science teachers’ understanding of complex systems is likely to improve their teaching of this domain.

5.4 Reasons behind Science Teachers’ Perceived Difficulties in Understanding and Teaching Complex Systems Ideas

To recap, it has been argued earlier that besides an empirical investigation of science teachers’ understanding and instructional practices in complex systems, it is equally important to understand the challenges facing science teachers in the learning and teaching of this domain. A review of the literature has showed that there is no research to systematically investigate the reasons hindering their understanding and teaching of
complex systems. This present research explores the reasons in science teachers’
difficulties in understanding complex systems using a representative sample of Grades 11
and 12 science teachers in Singapore and examines the reasons in their challenges in
teaching this domain using a group of six selected science teachers. It therefore offers
useful insight into the issues that need to be addressed to facilitate science teachers’
complex systems understanding and instruction in science classrooms.

From the survey, science teachers felt that they faced difficulties in understanding
complex systems because they had limited experience perceiving phenomena and
systems from this perspective and a lack of opportunity to learn about these ideas.
Perhaps it was due to these reasons that a handful of the teachers also felt that they
needed more time to change their current perception of scientific systems towards one
that is complex. As most science teachers indicated that they did not have prior
knowledge of complex systems, a complex systems perspective would represent a
fundamental shift in how they viewed scientific phenomena.

This finding indicates that not only there must be professional development for
science teachers to be familiar with complex systems, but also there must be sustained
efforts to continually provide professional learning opportunities for them to internalize
these ideas. According to complex systems researchers, the dominant scientific paradigm
– linear, reductionist and isolationist – that frames most people’s cognition often makes it
difficult for them to view systems and phenomena from other paradigms (Capra, 1996;
Wilensky & Resnick, 1999). This notion of the dominance of an existing paradigm dates
back to the seminal work of Thomas Kuhn (1962) who posits that people interpret
phenomena and solve problems within the context of the dominant paradigm. When anomalies occur, people tend to resolve them using the concepts and knowledge of the existing paradigm, rather than embark on the search for new explanations or see them from different angles. It is not to say that one’s perspective does not change, but time and effort will be needed for this change to internalize.

The interviewed teachers suggested three broad reasons why teaching complex systems might be difficult: students were unfamiliar with complexity in real-life situations; the underlying mechanisms in complex processes are obscure; and the current science syllabi and assessments do not emphasize complex systems. This finding hints at various but inter-related issues in incorporating complex systems into school science.

The teachers perceived that their students were unfamiliar with complex systems because their prior science education experiences were inadequate in getting them to perceive systems from a complexity perspective. In other words, the finding hints that students have limited exposure to this complexity approach of perceiving scientific systems throughout their formal pre-tertiary science education. This finding is not unexpected especially when the present findings about science teachers’ understanding of complex systems and the relationship between their complex systems understanding and instructional practices are taken into account. If these Grades 11 and 12 science teachers do not have a comprehensive complex systems understanding, it is unlikely that science teachers of lower grades will fare any better in conveying these ideas and this in turn may have resulted in students’ unfamiliarity with complex systems. This also suggests that
more professional development opportunities in complex systems should be provided for science teachers of all grade levels.

The second reason that students would find difficulty in visualizing the obscure underlying mechanisms of complex systems implies that science teachers may not be well-informed about the tools and resources to teach and learn complex systems. It has been described earlier in various sections that there are numerous promising research studies on visualization tools that can help learners see the mechanisms underlying the scientific phenomena (e.g., Ardac & Akaygun, 2004, 2005; Klopfer, 2003; Klopfer et al., 2009; Ryoo & Linn, 2012; Stieff, 2011; Tasker & Dalton, 2006; Yoon et al., 2012), providing representations of unobservable scientific phenomena. The fact that these teachers were not aware of such tools and resources may have been a result of a lack of professional development, or a lack of effort in promoting professional development, to enhance teachers’ subject matter knowledge and pedagogical content knowledge (i.e., how to teach) in complex systems.

The third reason that existing science syllabi and assessments do not emphasize complex systems is significant. In the introduction, it has been briefly explained that some science education researchers argue that the science curricula in other educational systems have yet to fully appreciate the complex nature of many scientific systems (Mitchell, 2009; Parafes, 2010; Resnick, 1994). It appears to be so in the Singapore context too. Indeed, from the video analyses of lessons in this present research, some complex systems ideas were not often conveyed explicitly even though the lessons being related to scientific complex systems. Despite the good work from many researchers
(e.g., Yoon, Klopfer et al., 2013) who have been exploring, designing and testing out science curricula based on complex systems ideas, teaching complex systems will remain a challenge in regular science classrooms if there is no concerted effort to emphasize this domain in the national science syllabi and assessments.

5.5 Limitations

There are three broad limitations in this study which can be addressed in subsequent research. The first two limitations relate to the methodology used. First, the analysis of the instructional practices was based on six teachers only. Although these teachers and the lessons recorded were representatively and purposively chosen for RQs 2, the teachers were nonetheless teaching different topics. The topics and concepts may have direct impact on the teaching of complex systems ideas. Some topics, such as evolution and kinetic theory of matter, may consist of more complex systems-related concepts than other topics such as forces. It will be prudent to compare how different teachers teach the same topic and how different topics across the whole subject are taught to determine the extent science teachers convey complex systems ideas in their lessons. While attempts have been made to gather from the larger sample information about how the teachers have incorporated complex systems ideas into their instruction, the data was limited in terms of the details. Observations and video recordings are still the more appropriate methods to collect data on the extent these ideas are taught.

Second, and somewhat related to the first, the relationship between teachers’ understanding and practice in complex systems was established in this research by comparing qualitatively the analyses from the teachers’ instructional practices and their
complex systems tests scores. However, this comparison was also limited by the number of teachers video-recorded and analyzed for their instructional practices. Although correlational analysis of the survey data converged to a similar finding, the findings can be made stronger with several more video analyses of other teachers’ instructional practices in other topics and their complex systems understanding.

Third, the conceptual links between teachers’ understanding and student learning, and teachers’ instructional practice and student learning are not explored in this research. As briefly stated in section 2.4, this research does not test the casual claim that teachers’ understanding and instructional practices of complex systems affect students’ learning of this field. Nevertheless, such an investigation will be necessary to connect the educational problem of students’ limited complex systems awareness directly to the teachers – what they know and how they teach the associated ideas. While there are studies in other science domains that pointed at the possibility of these relationships (e.g., Heller et al., 2012; Kanter & Konstantopoulos, 2010; see section 2.2.2), it is unclear if they hold true for the domain of complex systems. Investigating these relationships will be an appropriate topic for future research.

5.6 Conclusion

The 21st century is one of complexity and complex systems science has garnered tremendous attention from scientists and policymakers. This field has influenced several science education reform documents over the past decade and science educators and researchers have advocated complex systems instruction in school science for better science understanding. To borrow a quote from Lifitig (2008) who aptly describes the
importance of complex systems in 21st century school science in an editorial of a practitioner-focused journal,

...incorporating a systems approach in your science teaching and designing lessons with teachers in other curriculum areas will help produce science-literate citizens who understand the interrelatedness between the natural physical, chemical, and biological systems they study and society's political, technological, and economic systems (p.1)

Despite the emphasis and push for complex systems in science education for many years, science students have continued to show limited awareness in the complex nature of systems (Booth Sweeney & Sterman, 2007; Jacobson et al., 2011). This prompts a flurry of research and development into investigating and alleviating this educational problem.

This research examines the problem from a teacher perspective. The conceptual framework (Figure 1) in section 2.4 illustrates that teachers’ understanding may affect their students’ understanding and that this relationship may be mitigated by their instructional practices. Therefore, an empirical investigation of the state of our science teachers’ understanding of complex systems ideas, the extent these ideas are taught or conveyed in science classrooms, and the relationship between teachers’ understanding and instructional practices of these ideas is necessary in appreciating why students have poor understanding of complex systems.

The findings showed that Grades 11 and 12 science teachers did not have adequate and comprehensive understanding of complex systems. Complex systems were also not uniformly nor explicitly taught across the three science subjects in regular science classrooms. The research also suggested that there is a relationship between teachers’ understanding of complex systems and their instructional practices conveying the associated ideas. Collectively, these findings support the initial hunch that science
teachers may have inadequate understanding of this domain and this may influence their instruction of complex systems. More importantly, these various findings converge at two implications. First, the science education and research community should place equal emphasis on the teachers and the teaching of complex systems, and not simply on the learners and the learning of this domain. Existing research has largely skewed towards student learning, interventions and systems-oriented curricula at the expense of teacher learning and practice of complex systems. The teaching side of the teaching-and-learning equation should not be neglected. Second, professional development of science teachers will be necessary to enhance their capacity in teaching or conveying complex systems ideas. Noting that the teachers in this study come from Singapore, which has been touted as one of the quality educational systems in the world, it is likely that teachers in other developed countries in Europe, U.S. and some parts of Asia may be in similar situations.

Having ascertained that professional development of science teachers in complex systems is necessary to improve the current situation, how would such a professional development look and what may be some of the considerations? The science teachers in this study appeared to understand and convey some ideas better than others. Knowing the extent of understanding complex systems ideas and instructional practices of these ideas in regular science classrooms, professional development designers can use the information to plan and design appropriate programs. However, it is necessary to bear in mind that the professional development efforts should not only help promote teachers’ understanding of complex systems, but also provide strategies and approaches they can use to facilitate their students’ conceptions and foster commitment to the notion that
complex systems ideas are instructionally and conceptually important to the learning of science. Thankfully, the science education and research community can take heart that such professional development endeavor has been well underway; there are several research and development programs that have worked on teachers’ professional development in complex systems (e.g., Jacobson, 2001; Yoon & Klopfer, 2006; Yoon et al., 2014a; 2014b).

The empirical finding of the reasons hindering teachers’ understanding and teaching of complex systems also hints that a coordination of efforts – within and beyond professional development – will be required to carefully address the educational problem. From providing more learning opportunities and exposure to complex systems for teachers and students, designing teaching and learning aids to visualize the obscure nature of underlying mechanisms of complex systems, to putting more prominence to complex systems in existing science syllabi and assessments, these efforts can help alleviate some of the challenges science teachers face in understanding and teaching complex systems. However, to realize the intended results, that is, for complex systems to gain real traction in school science instruction, it will require reform efforts over extended time and at several levels: students and teachers; curriculum and learning and teaching resources; and school and district organizational support. This is in itself a complex endeavor – an endeavor the science education community should strive to continue working on.
Appendix A

Determining sample size and identifying clusters

Assuming that teachers’ complex systems understanding follows a normal distribution, Levy and Lemeshow (2008, p. 255) explain that the sample size required under simple one-stage cluster sampling, \( m \), can be determined using the following formula:

\[
    m = \frac{z_{1-(\alpha/2)}^2 M V_{1x}^2}{z_{1-(\alpha/2)}^2 V_{1x}^2 + (M - 1) \varepsilon^2}
\]

where \( M \) is the number of clusters (i.e., schools) in the population = 25;

\( z_{1-(\alpha/2)}^2 \) is the reliability coefficient for \( 100[1-(\alpha/2)] \) confidence. For 95% confidence, \( z_{1-(\alpha/2)}^2 = 1.96^2 \) (square of the z-score at 2 standard deviations);

\( \varepsilon \) is the maximum relative difference allowed between the estimate and the unknown population parameter. \( \varepsilon \) is specified as 0.2 or 20%.

\( V_{1x}^2 \) is the ratio of the variance of the parameter distribution of cluster totals, \( \sigma_{1x}^2 \), to the mean value of the parameter per cluster, \( \bar{X}^2 \). Or simply, \( V_{1x}^2 = \frac{\sigma_{1x}^2}{\bar{X}^2} \). As the quantities of \( \sigma_{1x}^2 \) and \( \bar{X}^2 \) are unknown parameters, the authors explain that these have to be estimated from other studies or guessed by means of intuition. The average \( V_{1x}^2 \) value from two different studies is applied to the above equation (Plate, 2010; Jacobson et al., 2011). These studies are chosen because the assessments used in these studies were adapted in this present research. It is therefore apt to use the results in these studies as proxies for estimating the unknown parameters. \( m \), the number of clusters, from this formula is six.
Appendix B

Ministry of Education
SINGAPORE

EDUN N32-07-005

31 October 2012

Mr Goh Sae-Ee Charles
42 Springdale Place
Singapore 786445

Dear Mr Goh,

INVESTIGATING SCIENCE TEACHERS’ UNDERSTANDING OF COMPLEX SYSTEMS

I refer to your application for approval to collect data from schools.

2. I am pleased to inform you that the Ministry has no objections to your request to conduct the research in 6 junior colleges/centralised institute, subjected to the following conditions:
   a) the approved research proposal is adhered to during the actual study in schools;
   b) the data collected is kept strictly confidential and used for the stated purpose only; and
   c) the findings are not published without written approval from the Ministry.

3. When conducting the data collection in the schools, please ensure that the following are carried out:
   a) consent is obtained from the Principals for the study to be conducted in the schools;
   b) teachers are informed that participation in the study is voluntary and they do not need to provide any sensitive information (e.g. name and NRIC No.);
   c) participation by the schools are duly recorded in Annex A; and
   d) the data collection in schools is completed within 6 months from the date of this letter.

4. Please show this letter and all the documents included in this mail package (i.e. the application form, research proposal and research instrument(s) marked as seen by MOE) to seek approval from the Principals and during the actual study.

Yours sincerely

Teo Kee Eng (Ms)
Head, Data Administration 3
Data Administration Centre
for Permanent Secretary (Education)

Note to Principal: Please refer to MOE notification PA/25/12 for the Guidelines on Data Collection from Schools.

Integrity, the Foundation • People, our Focus • Learning, our Passion • Excellence, our Pursuit.
Appendix C

The Principal, XXX

REQUEST TO CONDUCT PROFESSIONAL SHARING AT XXXX

Dear XXX,

Hope this letter finds you well. I have been closely following the college’s development all these years, and I am so glad to see that XXX has continued to stay on track in both character and academic development of her students. I believe this all boils down to the dedication of the teachers, the commitment of the heads, and the unswerving vision of her school leaders.

I am writing to you because I would like to request for your permission to conduct a professional sharing session for your science teachers on complex systems. Briefly, a complex system comprises of numerous parts and components that interact and connect with one another in multiple nonlinear ways, such that perturbations in one part of the system often cause unpredictable and large-scale effects throughout the system. For example, when a particular species is wiped out from the rainforest, it often leads to catastrophic outcomes to the entire ecosystem. Other scientific complex systems include the brain with its network of neurons, the weather system, gas systems, and electrical systems. The field of complex systems is a study of the common properties that transcend these diverse systems.

Traditionally, science has been taught as disparate topics with little coherence across the various systems, even within the same subject domain. Considerable research has shown that students and young adults (even teachers) have long been enculturated with a linear and centralized worldview that a single cause leads to a single effect, that outcomes are predictable when the causal factors are known, and that the patterns observed at the systemic level are the result of certain ‘drivers’ within the system. However, as the 21st century world is increasingly complex, scientists have argued that students should embrace a complexity perspective in science. Indeed, several research and educational agencies (e.g., the National Science Foundation, the National Research Council, and the American Association for the Advancement of Science) in the U.S. have urged for the instruction of ideas underlying complex systems ideas in science education. In Singapore, while science learning from a systems perspective is yet to be emphasized, the call for interdisciplinary approach to science instruction has undoubtedly been on-going for years.

I would like to share with your science teachers the big ideas in this field, and demonstrate the use of some computational tools that can facilitate learning and teaching of complex systems. These demonstrations will be anchored with complex systems examples from the current ‘A’ level science curriculum (e.g., evolution in biology, gas systems in physics, and chemical reactions in chemistry). The total commitment for the workshop is no more than two hours in total, but I would require a common session where I can address the entire science department or the individual science units collectively.

This sharing is actually part of my research, where I am investigating teachers’ understanding of complex systems. I want to know if our science teachers are knowledgeable in the big ideas of complex systems. The information I will gather can help inform future efforts in extending teachers’ capacity to teach complex systems. Therefore, prior to the professional sharing session, I will ask your teachers to complete a questionnaire comprising of some questions to assess their existing understanding of the domain, and after the session, an exit survey. Your teachers will be informed of the research component before the workshop.

I would be more than happy to come by the college to talk to you or your science head regarding this professional sharing session. Please feel free to contact me at sedm0253@yahoo.com. I look forward to your favorable reply.
Appendix D

Protocol 
Title of Study: Investigating Science Teachers' Understanding of Complex Systems
Principal Investigator: Dr. Susan Yoon, Graduate School of Education, University of Pennsylvania, Phone: (+1) 215-746-2626, Fax: (+1) 215-746-2618, Email: yoonsa@george.vu.edu
Student Investigator: Sao-Ee Goh, Graduate School of Education, University of Pennsylvania, Phone: (+65) 90238893, Email: sip@sohlin.une.com

TEACHER CONSENT FOR PARTICIPATION IN AN OBSERVATIONAL INVESTIGATIONAL STUDY

Invitation to Participate: You are being asked to participate in a research study conducted by a student of the University of Pennsylvania, Graduate School of Education, for his Ph.D. dissertation. This is because you are a teacher teaching Grades 11 and 12 (or A-level) science subjects in Singapore. The research study is titled Investigating Science Teachers' Understanding of Complex Systems. The duration of the research is 1 Oct 2012 to 1 May 2013.

Purpose: This study seeks to investigate the extent science teachers understand about an emerging field of science known as complex systems. Specifically, it aims to find out what teachers understand about the key complex systems ideas, how, if any, these ideas are incorporated into their instructional practice, and why they may encounter difficulties in interpreting and teaching these ideas.

Procedures: You will be observed on your classroom teaching of complex systems-related topics and concepts for four to six periods. The topics to be observed will be discussed with you. During the observation, you may be video-or audio-recorded, and transcripts of these recordings will be written up. Observation notes will also be taken. After the observations, you will be interviewed on the difficulties you face in teaching science concepts from a complex systems perspective.

Risks: There are no potentially harmful risks related to participating in this study.

Benefits: Potential benefits to participants include an increased awareness of what complex systems are.

Withdrawal: Your participation is completely voluntary and you may withdraw from the study at any time.

Alternatives: You may choose not to participate in this study entirely or participate in only a part of it.

Compensation: You will not be compensated for your participation in this study.

Confidentiality: All information collected in this study will be kept private and you will not be identified by name or school. Authorized representatives of the University of Pennsylvania Institutional Review Board (IRB) committees which are charged with protecting the rights and welfare of research participants, may be provided access to research records that identify you by name and school. The digital and physical data from this study will be kept in locked storage. Only the student researcher in this study will have access to these data and they will be destroyed by October 31, 2017.

Subject Rights: If you wish to receive further information regarding your rights as a research participant, you may contact either of the investigators (see top of page for contacts) or the Directory of Regulatory Affairs at the University of Pennsylvania at (+1) 215-893-2014.

Conclusion: You have the opportunity to ask questions and have had them answered to your satisfaction. You have read and understand the consent form. You agree to participate in this study. Upon signing below, you will receive a copy of the consent form.

Name of teacher participant __________________________ Signature of teacher participant __________________________ Date ____________

Name of investigator __________________________ Signature of investigator __________________________ Date ____________
Appendix E

UNDERSTANDING OF COMPLEX SYSTEMS QUESTIONNAIRE

This questionnaire aims to find out how you interpret complex systems. Analyses of your responses can reveal your beliefs about such systems. This questionnaire will require 45 minutes to complete. Instructions will be given on how to proceed for each section. There are 5 pages in this questionnaire.

Please do not answer any of the questions until after the instructions have been given.

SECTION A: Demographic Information

1. Name: (optional) ____________________ 2. School: ____________________________

3. Gender: (circle where appropriate) M / F 4. Teaching subject(s): _______________ _______________

5. Number of years of teaching science: __________

6. a) What do you major in (i.e., your undergraduate degree)? ____________________

   b) What is your post-graduate degree (if any) in? ________________________________

7. Are you aware of complex systems, complexity, complex science, complexity science?

   Yes / No →

   If yes, please briefly describe what you know about this field?

   ________________________________

   ________________________________

   ________________________________

   ________________________________

   ________________________________
SECTION B: Natural Systems

1. Models of ants
   Place a tick in the box next to the model you think best represents ant foraging behavior.

<table>
<thead>
<tr>
<th>Model</th>
<th>Best describes what I believe about ant foraging behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video 1: Worker ants leave their colony and wander around randomly to find food. Upon finding a food source, they return to the nest with bits of the collected food, and deposit a chemical trail that decreases in intensity with time. Other ants on picking up this trail move toward the food source.</td>
<td></td>
</tr>
<tr>
<td>Video 2: A leader ant first goes out from the colony to find food. When she finds a source, she picks up some and deposits a chemical trail when she returns to the nest. The worker ants then follow the trail to get more food until there is no more food.</td>
<td></td>
</tr>
</tbody>
</table>

Explain your choice briefly. __________________________________________
____________________________________________________________________

2. Birds flocking
   Select the statements you believe describes the phenomenon you have just seen in the video. “I believe birds form and stay together in flocks because…” (tick at least two statements)

   a. There are certain ‘leader’ birds that the others follow to form flocks.
   b. Birds align themselves as they fly by steering towards the average heading of their local flockmates.
   c. Birds form flocks to protect themselves by being in a group.
   d. Leader birds communicate with the other birds to tell them which way to go using special sounds.
   e. A flock is held together because the birds will steer to move toward the average position of local flockmates.
   f. As birds fly, they steer so that they are not too close to each other.
   g. There are no leader birds; any bird may be at the head of the flock at any given time.
   h. Birds form flocks because they need to migrate.
   i. Birds try to stay with other birds that are like themselves.
   j. Birds form flocks because they get scared by other animals near the group and fly away.
SECTION C: Socio-scientific System

1. You are now given a short article on a fishery issue. Spend 5 minutes to read.

2. You will now be given instructions on how to construct a casual map which illustrates the relationships between concepts.

There are three possible relationships between concepts.

Legend:  

( + ) An increase in A increases B; or a decrease in A decreases B  
( − ) An increase in A decreases B; or a decrease in A increases B  
( 0 ) A does not affect B, or you are unsure of the relationship

Example: Car sales, car prices, and number of cars on the road

3. From the list of concepts below, circle those you think is necessary to help you fully explain the issue to your students.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>G</th>
<th>H</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae blooms in coastal sea</td>
<td>Amount of samaki caught</td>
<td>Demand for omega-3 food supplement</td>
<td>Demand for animal feed</td>
<td>Predatory marine animal and bird population</td>
<td>Production from fish-oil competitors</td>
<td>Public information to increase omega-3 intake</td>
<td>Samaki population</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of competing products (e.g., soybeans, vegetable oils)</td>
<td>Samaki industry profits</td>
</tr>
</tbody>
</table>
4. Based on the concepts you have chosen in 3, construct your causal map below. You may just use the alphabet representing each concept on your map.
SECTION D: Ecological System

A park ecosystem consists of both living (biotic) and non-living (abiotic) elements. These elements (e.g., animals, plants, water, soil, rocks) interact with one another in various ways. Imagine a flock of thirty geese arriving in MacRitchie Reservoir where geese have not lived before. Describe how the addition of these geese affects the ecosystem over time.

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Thank you for your responses!
Appendix F

Script for administration of questionnaire

Introduction

Thank you for participating in this sharing session on complex systems. My name is Sao-Ee, and I am currently an advanced doctoral student at the University of Pennsylvania. Many of us may have some idea of what complex systems are, and we will get deeper into that in a while.

Before we begin, I would like you to fill up a questionnaire to find out how you interpret systems. This will allow me to know what your beliefs are so that I can customize the session better. This is also part of my dissertation study.

There are four sections to this questionnaire, and it should take about 45 minutes. We will be doing each section together. So I would request that you do not to jump ahead to the next section when you are done. Do you have any questions?

Section A (3 minutes)

First, please fill in Section A. This section has 7 questions which ask for some information about you as a teacher. It should not take you too long, about 3 minutes will do. You may begin.

[after 3 minutes]

Section B (10 minutes)

Let’s go on to Section B. We often see ants crawling around our house, and they somehow mysteriously appear when there is food lying around. I would now be showing you two videos of models on how ants are believed to behave as they look for food. This is the first video.

[Play Video 1: 30 s]

In this video, worker ants leave their colony and wander around randomly to find food. Upon finding a food source, they return to the nest with bits of the collected food, and deposit a chemical trail that decreases in intensity with time, as shown by the changing color. Other ants on picking up this trail move toward the food source. Now, here’s the second model.
In this video, a leader ant first goes out from the colony to find food. When she finds a source, she picks up some and deposits a chemical trail when she returns to the nest. The worker ants then follow the trail to get more food until there is no more food.

Now, place a tick in the box next to the description you think best represents the food-finding behavior of ants. After you have selected, give a brief reason for your choice in the space below. You have 3 minutes for this question.

Now, onto birds. You probably have seen birds flying in formation – whether it is a small group of migrating geese flying in a V-shape or thousands of starlings swooping and diving together. This question asks you for your thoughts on how birds form and stay together in flocks.

Let me first show you a short video clip on birds flocking. This is to let you visualize what I am referring to.

Now, there are 10 statements which describe how such formation occurs. Please read through all the statements and choose at least two statements you believe to be true. You can tick more two than statements.

Section C [17 minutes]

Now I will give you a short article to read. You will spend a couple of minutes to read the article. After that time is up, you will put that article aside, and we will go through a short series of exercises relating to the article. You may begin reading.

Ok, please keep the article aside. I will ask you to construct a causal map shortly. First, what is a causal map? It is a technique that researchers can use to evaluate an individual’s mental causal structure of a phenomenon. In other words, it can be used to portray one’s understanding of the cause-and-effect relationships amongst concepts.

I would like you to turn to page 4 of your questionnaire. There are three possible relationships between concepts. I will use concepts related to cars as an example. [the following three relationships should be written on board or shown as powerpoint slide]

1) An increase in A leads to an increase in B. Or a decrease in A leads to a decrease in B.
For example, an increase in car sales causes an increase in the number of cars on the road.
For this same-direction relationship, you will indicate with a ‘+’ sign.

2) An increase in A causes a decrease in B. Or a decrease in A causes an increase in B.
   For example, an increase in car prices causes a decrease in car sales.
   For this opposite direction relationship, you use a ‘-’ sign.

3) No relationship.
   For no relationship, indicate with a ‘0’.

I would also like you to consider the inverse of the relationships. That is, B becomes the cause, and A becomes the effect. Would an increase in car sales lead to a decrease, increase or have no relationship to car prices?

Do you have any questions concerning how to construct a causal map?
Now, imagine you are presenting the issue of samaki to a class in which the students know nothing about the issue. What aspects of the situation would you relate to the students so that they would get the most complete understanding of the issue?

On page 3, there are 10 concepts. Go through the list of concepts and circle the concepts or things you would discuss with the class. The goal here is to give the class the fullest understanding possible. But, choose only those concepts that express the things you can explain. In other words, things you actually understand. You may pick as many concepts as you like.

After you have picked the concepts, please construct your causal map in the box below. You have 10 minutes to complete your map, but I can give you more time for those who have chosen everything!

Section D [10 minutes]

Ok, I see that most of you are done. Great job! I would like those of you who are done to proceed to answer the last question in Section D. This is an open-ended hypothetical question. Please attempt the question as fully as you can. Don’t worry if you cannot recall the scientific terms to use. Just use plain simple English. I am not looking at how good your ecological knowledge is, but rather how you interpret systems. You have 10 minutes to do this question.

When you are done, please make sure your demographic information in Section A is completed, and you can give them to me. And you can take a short break after this.
Appendix G

Samaki: An Ecological and Industrial Treasure (adapted from Plate, 2006)

Samaki, a larger cousin of the herring, may be the most important fish you’ve never heard of. No one eats samaki directly. They are oily fish filled with tiny bones. However, they still find their way to our dinner tables through indirect routes.

First, they provide an ecological link between microscopic plankton and large predatory fish. In other words, they eat the plankton and, in turn, become an important source of food for many large, high valued fish, including bass, cod, swordfish, bluefish, and tuna. Second, they are ground up, dried, and used to make feed for poultry, pigs, beef, and even farmed fish, providing an important source of protein for these farm-raised animals as well. Recently, a third path has been added. The American Heart Association declared in 2002 that people should consume Omega-3 fatty acids to prevent heart disease, leading to an increase in the use of these oils as food supplements for humans as well.

The usefulness of samaki in animal feed and food supplements has made catching samaki big business. Literally millions of pounds of samaki are caught every year for industrial use. In fact, samaki has become so useful to industry that some suggest this once abundant fish is in danger of being overfished. Analysts explain that leaders in the samaki industry have experienced decreased profits and even losses over the past decade, and this is one sign that the samaki population has been significantly reduced.

However, FishX – one of the largest suppliers of samaki-based fish meal and fish oil products in the U.S. – suggests that samaki population is doing fine. They explain that the reduced profits were due to factors that were not related to the health of the fishery. First, prices of their products are highly affected by the amount of samaki caught by their international competitors. High catch levels elsewhere in the world lower the price of FishX’s products. Second, FishX must compete with alternative products. For example, unusually low prices in soybeans and vegetable oil, which are also protein sources, from 1999 to 2001 lowered FishX’s sales for those years. FishX officials point out that the availability of these competing products drove down the price of their own products. The result was a decrease in their profits.

But despite FishX claims, many people outside the fish-meal industry are concerned about possible decreases in the samaki population, because samaki are also important ecologically. Samaki are a major source of food for larger fish and other marine animals. Scientists have also linked decreases in samaki in some ecosystems to declines in the bird population in those systems. In addition to being an important source of food, samaki are filter feeders that help control algal growth in coastal waters. Adults can be seen swimming in tightly packed groups with their mouths open, filtering out algae species that many other fish would not eat. Some people place great importance in the samakis’ feeding habits. For example, declines in samaki populations have been linked to algal blooms along coastal waters. That’s where the algae grow so thick that they kill everything else in the area. In this sense, samaki not only provide a food source for valuable fish species, but also make the coastal waters a better place for fish to live.
Appendix H

Perception questionnaire
This questionnaire is an exit survey to determine which of the complex systems ideas you have learned are the more difficult ones, and why. This is to help in the planning of future professional development in complex systems.

This survey will take approximately 10 minutes.

Part A

1. Of these four categories of complex systems ideas you have learned, rank them (1 = least difficult … 4 = most difficult) in order of your difficulty in understanding.

<table>
<thead>
<tr>
<th>Nonlinearity and non-determinism</th>
<th>Open and dynamic nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence and self-organization</td>
<td>Decentralization</td>
</tr>
</tbody>
</table>

Part B

2. Reflect on your teaching in the past six months, particularly of topics related to systems, are these complex systems ideas incorporated in your teaching?

Yes / No (please circle)

If yes, please state the topic(s) in which this was done,

Topic(s): _________________________________

and briefly describe how this was done.

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

Please turn over
Part C

4. In your personal capacity, do you find these complex systems difficult to understand?

Yes / No (please circle)

If yes, why do you feel they are difficult to understand? Please check the reason that applies to you. You may check more than one reason.

<table>
<thead>
<tr>
<th>Reason</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The current science curriculum does not emphasize these ideas.</td>
<td></td>
</tr>
<tr>
<td>2. I do not believe that these ideas are scientifically valid.</td>
<td></td>
</tr>
<tr>
<td>3. I need to learn about these ideas by experiencing with models depicting complex systems.</td>
<td></td>
</tr>
<tr>
<td>4. I feel that these ideas are not generally accepted in the scientific community.</td>
<td></td>
</tr>
<tr>
<td>5. These ideas somewhat contradict ideas and concepts in the current science curriculum.</td>
<td></td>
</tr>
<tr>
<td>6. I have trouble perceiving most scientific phenomena with these ideas.</td>
<td></td>
</tr>
<tr>
<td>7. I require more learning opportunities that convey these ideas.</td>
<td></td>
</tr>
<tr>
<td>8. These ideas do not fit into the topics in the science curriculum.</td>
<td></td>
</tr>
<tr>
<td>9. I need additional information about these ideas.</td>
<td></td>
</tr>
<tr>
<td>10. I believe that such cross-disciplinary ideas cannot exist.</td>
<td></td>
</tr>
<tr>
<td>11. Understanding the ideas require a fundamental shift in how I view scientific phenomena.</td>
<td></td>
</tr>
<tr>
<td>12. It will take time to change my perception of complex systems.</td>
<td></td>
</tr>
</tbody>
</table>

Other reasons (please explain): __________________________________________

_______________________________________________________________________

_______________________________________________________________________

_______________________________________________________________________

Thank you for your participation.
Appendix I

Interview protocol

Introduction

Thank you for taking your time in this interview. Based on the classroom observations on the topic: [insert name of topic]. I would like to ask you a few questions about what you taught, how you taught the content, and why you taught it that way. I want to understand the underlying perspective you have about this complex systems-related topic through your teaching.

We will probably be spending about 45 minutes to an hour. First, I will describe to you what you did during the lesson on [insert the concept taught].

I would like to audio record this interview. This is purely to facilitate my analysis later on. There should not be any confidentiality issue as I will not be sharing who said what explicitly in my dissertation. Do you have any objections to this? And do you have any questions before we begin?

[Start recording at this point. If interviewee objects, provide reassurance but do not force the issue.]

Description of lesson

[From a preliminary analysis of the observations, select and describe one to two typical teaching episodes that suggest a complex perspective.]

Could you explain to me why you teach [insert the concept taught] this way?

[Probe to confirm teacher’s complex perspective of the concept. After determining the perspective, proceed with the interview proper as outlined in the following heuristic.]
Interview heuristic

Determine if teacher has a complex systems emphasis in teaching the particular concept

Complex

Is teacher aware of his emphasis?

Yes

Ask teacher to explain what he means.

Correct

No

Explain to teacher what this emphasis mean.

Incorrect

Clockwork

Is teacher aware of his emphasis?

Yes

Ask teacher if he experiences difficulty in understanding of the topic from this emphasis, what these difficulties are, and why they may occur.

Correct

No

Explain to teacher that there is another approach to teaching the concept with a complex systems emphasis.

Incorrect

Ask teacher if he anticipates difficulty in understanding of the topic from this emphasis, what these difficulties are, and why they may occur.

Correct
Appendix J

Complex Systems Ideas Categorization Manual (CSICM)

Analyzing Response With Respect to Component Beliefs in Clockwork vs. Complex Systems Frameworks

For this dataset, teachers have provided responses for the following question: "Imagine a flock of geese arriving in a park in Philadelphia, where geese have not lived before. Describe how the addition of these geese to the park may affect the ecosystem over time. Consider both the living and non-living parts of the ecosystem." The unit of analysis is the entire response. Each response can be rated in one of three belief orientations for each of the four categories of complex systems ideas:

1. Clockwork
2. Somewhat complex
3. Complex

Epistemological underpinnings of clockwork and complex systems frameworks

Clockwork
A clockwork belief is centrally defined by Cartesian mechanism where the world and its constituents are generally viewed as machines. It is based on the method of analytic thinking, which consists in breaking up complex phenomena into pieces to understand the behavior of the whole from the properties of its parts. In other words, the material world can in principle be understood completely by analyzing it in terms of its smallest parts. Each of the parts is typically not considered in relation to the whole. There is an assumption that there are pre-determined universal laws governing all action and that these laws exist in an objective reality awaiting human discovery. Methodologically, it is rational, linear and logical.

Complex
A complex belief is centrally defined by systems thinking in terms of connectedness, relationships and context. According to the systems view, the essential properties of an organism (or complex system), are properties of the whole, which none of the parts have. They arise from the interactions and relationships among the parts. Systems thinking concentrates on the basic building blocks of the system, their functions and organization, and putting these functions and organization into the context of a larger whole. Methodologically, it is non-linear, non-deterministic, and multi-dimensional. It also takes account of randomness in the system.

Category of Complex Systems ideas, Belief, Description and Examples
Each section from A - D has the same structure: category of complex systems ideas; a brief description of how the category is considered under a clockwork and a complex belief; sign-posts (words or phrases that signal a clockwork or complex belief); and exemplar rationales illustrating each of the 1 - 3 ratings to be assigned.
**Section A: Nonlinearity and non-determinism**
Description: The emphasis is the predictability of the effects caused by the geese in question, and the nonlinearity in reasoning of the complex phenomenon.

<table>
<thead>
<tr>
<th>Clockwork (Level 1)</th>
<th>Somewhat Complex (Level 2)</th>
<th>Complex (Level 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response implies:</td>
<td>Response implies either (i) or (ii) of Level 3.</td>
<td>Response implies:</td>
</tr>
<tr>
<td>(i) determinism: the way in which a part operates or affects other parts is completely predictable. No alternative is offered in the response. (ii) linear interactions: the interactions between parts are linear with no feedback mechanisms.</td>
<td>(i) non-determinism: the way in which a part operates or affects other parts is completely unpredictable. There are more than one possibilities suggested in the response. (ii) nonlinear interactions: the interactions between parts are non-linear with feedback mechanisms.</td>
<td></td>
</tr>
</tbody>
</table>

**Exemplars**

The geese are generally herbivores, so the aquatic plants decrease in population. They are also known to clear garbage which reduce the amount of garbage.

*[tone is deterministic; no feedback mechanisms present]*

The geese will compete with the birds or any other animals that are already in the reservoir for food. So temporarily, the amount of food that the birds eat will decrease. The non-geese bird population [1st alternative] might decrease since there is a fierce competition for food. The waste from geese [2nd alternative] might increase nitrogen containing compounds in the water. This leads to an increase in the growth rate of algae. When there're more algae in the water, this will lead to a decrease in oxygen level in the water, so aquatic microorganisms may decrease in population. A drop in aquatic microorganisms will affect the amount of food available in the food chains or web. This will result in a decrease in fish population --> geese might not have that much food after a while [feedback evident here].

**Signposts / Remarks**

[i]: will, would

[i]: may, might, probably, possibly, either… or, perhaps, if.

[ii]: feedback, cyclic pattern, cycle, indication of population increase and decrease.
**Section B: Open and dynamic nature**

Description: This refers to the non-bounded nature of the system in question, and the dynamism of the mechanisms that underlie the phenomena.

<table>
<thead>
<tr>
<th>Clockwork (Level 1)</th>
<th>Somewhat Complex (Level 2)</th>
<th>Complex (Level 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Response implies:</strong> (i) static events: the system is composed of static events. While perturbations in the system cause change(s) to occur, the change(s) terminates once an outcome is achieved (i.e., a definite end). (ii) bounded system: only obvious components within the system matters and are considered.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Response implies either (i) or (ii) of Level 3.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Response implies:</strong> (i) dynamism: the system is an on-going, dynamic process. System continues to be in a state of flux. The parts continue to adapt or evolve over a long period of time. (ii) open system: less-obvious components within or outside of the system are also considered.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Exemplars**

Some organisms in the water may multiply and flourish due to the introduction of waste of geese. The rocks may also be contaminated with waste excreted by the geese, causing excessive buildup of nitrates, and insects that crawl or fly would not find it habitable. *[no evidence of continual changes and no components outside the immediate system are considered]*

 *[evidence of i]* if there are no existing predators present in the ecosystem, the geese will be able to survive till sexual maturity and experience reproductive success efficiently. There will be a huge increase in the population of geese in a short time. This in turn leads to a decrease in the number of other organisms who are being out competed. However, once the population of geese reached a certain size, the amount of resources would deplete subsequently till an equilibrium is reached. Then the population of the geese will stabilize with the environment until further changes in the environment.

 *[evidence of ii]* Geese's droppings may become a nuisance to humans and their presence a disturbance to dating couples on hot date. Kids may enjoy feeding geese with bread and so geese become dependent on humans and lose their animal survival instincts; may also become a public nuisance (similar to monkeys).

**Signposts / Remarks**

[ii]: Immediate system in question is the reservoir (i.e., a body of water surrounding by a man-made park)  

[i]: evolve/evolution; cycle; genetic variation; indication of variation over a long period of time; increase then decrease until equilibrium is reached; symbiotic exchange  

[ii]: forest encompassing the immediate reservoir park, animals from other ecosystems, climate patterns; humans; minerals in the rocks; viruses/diseases/toxins introduced into the system by the geese
### Section C: Emergence and Self-Organization

Description: The focus is the nature of the systemic pattern formation.

<table>
<thead>
<tr>
<th>Clockwork (Level 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response implies:</td>
</tr>
<tr>
<td>(i) the action causes localized changes only with no cascading effects.</td>
</tr>
<tr>
<td>(ii) there is indication that the change(s) is caused intentionally.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Somewhat Complex (Level 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response implies either (i) or (ii) of Level 3.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Complex (Level 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response implies that:</td>
</tr>
<tr>
<td>(i) the action can cause both large-scale and local changes, with at least two levels of cascading effects.</td>
</tr>
<tr>
<td>(ii) there is no indication that the change(s) is caused intentionally.</td>
</tr>
</tbody>
</table>

### Exemplars

- **The geese may choose to remain behind and ‘fight it out’ with the local populations.** If the eating habits of both the geese and other animals are the same, the population of that group of animal will decrease. If their eating habits are completely different, the population of that group of animal remains the same.

- **As there are no potential predators,** the population of geese will multiply which leads to a drastic increase in their population. This might lead to a drastic decrease in population of fishes, when fish population decrease drastically (towards extinction kind of drastic) [evidence of i]. The population of geese will also decline due to a decrease in their prey (fishes). In the long run, the algae's population will multiply drastically due to lack of fish [evidence of i] and this will block off sunlight and all creatures die. The reservoir will become "dead" with only algae!

### Signposts / Remarks

- [i]: localized changes only
- [i]: A \(\rightarrow\) B is only one level of cascading effects.
- [ii]: Any indication of intentionality on the part of geese.

- Do not mistake cascading effects with agents. E.g., geese and geese waste count as one agent but they can contribute to two cascading levels: geese increases geese waste in water, which increases algae population. That is two levels of cascading effects.

- [i]: climate change, big change in ecosystem (e.g., becomes a marshland), extinction, interbreed, new species, overpopulation, threatening disease (e.g., avian flu)

- [i]: A \(\rightarrow\) B \(\rightarrow\) C is two levels of cascading effects

- [i]: Competition for resources or space would imply two levels of cascading effects.

- [i] Food chain would imply at least two levels of cascading effects.
**Section D: Decentralization**
Description: The focus is how the system obtains its order – centralized (by certain authority or controlling body), or decentralized (no single leader).

<table>
<thead>
<tr>
<th>Clockwork (Level 1)</th>
<th>Somewhat Complex (Level 2)</th>
<th>Complex (Level 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response implies centralization whereby the order in the system is controlled by one central agent, that is, all actions are determined by the geese.</td>
<td>Response implies some decentralization whereby the order in the system is controlled by two components (i.e., one more besides the geese).</td>
<td>Response implies decentralization whereby the order in the system is controlled by more than 2 components (i.e., two more besides the geese).</td>
</tr>
</tbody>
</table>

**Exemplars**

The geese will bring about more visitors to the park, which can both decrease the space in the park and increase the amount of waste.

\[ \text{geese} \rightarrow \text{visitors, so only geese} \]

Geese decrease the plants which affect other animals. The geese will decrease the fish population, which will in turn decrease the geese population due to lack of food. The decrease in fish can affect other animals which depend on the fish for food.

\[ \text{geese} \rightarrow \text{fish} \rightarrow \text{other animals, so geese and fish are the central agents} \]

Geese droppings might fertilize the grass there; thus enhancing the growth of grass. This might increase the population of insects that feed on grass though. With an increase in such insects, the population of geese and even other types of birds which are not threatened by the geese population will also increase.

\[ \text{geese} \rightarrow \text{grass} \rightarrow \text{insects} \rightarrow \text{geese and other birds, so geese, grass, and insects are the central agents} \]

**Signposts / Remarks**

Geese, geese waste, and geese noise count as only 1 central agent (geese).

A \(\rightarrow\) B \(\rightarrow\) C means there are 2 agents (A and B).

Competition, food chains, and symbiotic exchange would imply at least two agents.

A \(\rightarrow\) B \(\rightarrow\) C \(\rightarrow\) D (A, B, and C are agents)

A \(\rightarrow\) B \(\rightarrow\) A; A \(\rightarrow\) C \(\rightarrow\) D (A, B, and C are agents)

Soil, water, and rocks can be considered as agents too if they cause an effect.
Appendix K

Complex Systems Ideas Categorization Manual – Version B (CSICM-B)

Analyzing Video Transcripts With Respect to Complex Systems Ideas

Instructional practices of teachers have been transcribed and chunked into teaching episodes. A teaching episode is a unit of analysis, understood as a sequence of turns that spans a length of time focusing on a topic or an activity (Gee, 2005). Each episode roughly described the teaching of one particular science concept, solving one problem or addressing a question. It captured what and how the concept was taught, what examples or analogies the teacher used in the explanation, among other content-related aspects of their practice. An episode began when the teacher brought in a new scientific concept or got the class to solve a new problem. Within an episode, the teacher might ask questions, show an applet or demonstration, explain the concept, get students to respond or present their solutions to a problem, and/or engage the class in a discussion. An episode ended when the teacher moved on to a new concept or problem. Each episode can be rated as “2: explicitly described or explained,” “1: implied” or “0: not observed/implied” for each of the four categories of complex systems ideas.

Epistemological underpinnings of complex systems frameworks

Complex
A complex belief is centrally defined by systems thinking in terms of connectedness, relationships and context. According to the systems view, the essential properties of an organism (or complex system), are properties of the whole, which none of the parts have. They arise from the interactions and relationships among the parts. Systems thinking concentrates on the basic building blocks of the system, their functions and organization, and putting these functions and organization into the context of a larger whole. Methodologically, it is non-linear, non-deterministic, and multi-dimensional. It also takes account of randomness in the system.

Category of Complex Systems ideas, Belief, Description and Examples
Each section from A - D has the same structure: category of complex systems ideas; a brief description of what the complex belief is about; sign-posts (words or phrases that signal a complex belief); and exemplars illustrating Levels 1 and 2 for the category.
**Section A: Nonlinearity and non-determinism**

Description: The emphasis is the predictability of the effects caused by the geese in question, and the nonlinearity in reasoning of the complex phenomenon.

0: Not implied/observed

Ideas of non-determinism and nonlinearity not observed nor implied in teaching episodes or written descriptions.

1: implied and 2: explicitly described or explained

Teaching episodes or written descriptions implying (1) or explicitly describing or explaining (2) ideas of

(i) non-determinism: the way in which a part operates or affects other parts is completely unpredictable. There are more than one possibilities suggested in the response; and/or

(ii) nonlinear interactions: the multiple interactions between parts are non-linear with feedback mechanisms.

<table>
<thead>
<tr>
<th>1: implied</th>
<th>2: explicitly described or explained</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exemplars</strong></td>
<td><strong>Exemplars</strong></td>
</tr>
<tr>
<td>(a) when the two carts collide and then they stick together, they will, the force increases to a max and then decreases to zero, and they move. So in real life, it won't be a constant force. As it enters, the retarding force increases and as the bullet starts to slow down, the retarding force reduces. [nonlinearity but no reference to what the feedback mechanism is and why]</td>
<td>(a) One of the mechanisms of neutral theory is genetic drift. Ok? The commonality between both is that it is random. I say it's random, it means that there isn't any selection. [non-determinism]</td>
</tr>
<tr>
<td>(b) mutation can lead to speciation with environmental pressures [non-determinism in the concept of mutation but no specific reference to the random changes in the genes]</td>
<td>(b) If you just look at this particle, the particle is travelling in quite a straight line right? How about if I have 1,000 particles and I track the motion of this one. How would that movement be different? This one [referring to the 16 particles diagram] can still travel in quite a straight line. But if I have 1,000 particles here, what will happen?... It becomes a bit random… will the particles still make very long distance straight line movement? It won't right? Because it's bumping into stuff. [nonlinearity; non-determinism]</td>
</tr>
</tbody>
</table>

**Signposts**

Teaching a concept or topic with an implicit reference to feedback mechanisms, non-constant effect or cause, and randomness.

[i]: words that imply uncertainty - may, might, probably, possibly, either… or, perhaps, if, stochastic, probabilistic; random

[ii]: words that imply feedback, cyclic pattern, cycle
### Section B: Open and dynamic nature

**Description:** This refers to the non-bounded nature of the system in question, and the dynamism of the mechanisms that underlie the phenomena.

0: Not implied/observed

Ideas of dynamism and open nature are not observed nor implied in teaching episodes or written descriptions.

1: implied and 2: explicitly described or explained

Teaching episodes or written descriptions implying (1) or explicitly describing or explaining (2) ideas of

(i) dynamism: the system is an on-going, dynamic process. System continues to be in a state of flux. The parts continue to adapt or evolve over a long period of time; and/or

(ii) open nature: environment surrounding the system and other less-obvious components within or outside of the system are also considered.

<table>
<thead>
<tr>
<th>1: implied</th>
<th>2: explicitly described or explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) The key idea is that you vary the resistance of variable resistor so that you change the voltage taken here and then the current will change accordingly. For the thermistor... a thermistor reacts to what? Change in temperature. When I change the temperature, the V across here, the thermistor...changes. [open nature; suggested but not explicit that the electrical system is affected by the external environment]</td>
<td>(a) So what are dissipative forces? These are forces whereby energy is lost from a system. ok? Whenever there is motion. When motion takes place and energy is lost, there must be presence of dissipative forces. … [open nature]</td>
</tr>
<tr>
<td>(b) when light increases, the resistance of LDR will drop. [open nature; but not explicit in connecting to the influence of external environment on system]</td>
<td>(b) Over time, over billions of generations, after many rounds of selection, and differential survival, and differential reproduction, this will be roughly the gene pool for the species on XXX's island. Gene pool consists of yellow and black alleles. Over time we see that the gene pool becomes very, very different. And this will eventually lead to speciation. [dynamism]</td>
</tr>
<tr>
<td>(c) the reaction will continue until dynamic equilibrium is reached. [dynamism; but only implying that the system continues in a state of flux]</td>
<td>(c) … if you look at this [1000 particles in a box], particle is originally here, then after a long while right? [Attempting to find the end point] err… I don't even know where is it? I can't locate where it’s, but it's only after a long, long, long while right, that maybe, that particle will just move by chance to here. [dynamism]</td>
</tr>
</tbody>
</table>

**Signposts**

Teaching a concept or topic with an implicit reference to continual changes and the influence of less-obvious components or the surroundings.

**Signposts**

[i]: evolve/evolution; cycle; genetic variation; indication of variation over a long period of time; increase then decrease until equilibrium is reached; constant state of flux; dynamic equilibrium

[ii]: beyond the system; surroundings; hidden components
Section C: Emergence and Self-Organization

Description: The focus is the nature of the systemic pattern formation.

0: Not implied/observed

Ideas of emergence and self-organization are not observed nor implied in teaching episodes or written descriptions.

1: implied and 2: explicitly described or explained

Teaching episodes or written descriptions implying (1) or explicitly describing or explaining (2) ideas of (i) emergence: a localized action can cause large-scale (and local) changes. (ii) self-organization: there is no indication that the change(s) is caused intentionally.

<table>
<thead>
<tr>
<th>1: implied</th>
<th>2: explicitly described or explained</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exemplars</strong></td>
<td><strong>Exemplars</strong></td>
</tr>
<tr>
<td>(a) if this molecule is chiral, the products should also be chiral. This one, chiral if it's 100 percent of this product. The sample is optically active. If I have 100 percent of this [refers to non-inverted product], it is also optically active. But if I have a mixture, fifty-fifty, the mixture of the two molecules will give me a sample, which is optically NOT active. [emergence; hinted but not explicit]</td>
<td>(a) What is non-random mating? It suggests that the black likes to mate with the black and the red likes to mate with the red… So non-random mating will increase homozygosity. [emergence]</td>
</tr>
<tr>
<td>(b) A beam of electrons enters a region where there are magnetic and electric fields, and it passes straight through without deflection. Sketch the direction of electrons, its velocity with respect to the orientation of the E-field it is in. You have an electron going through, it will curve up within the plates. Within it, curve will be parabolic. So if you want it to go straight out. This E-field, what is the direction of force due to the E-field? [emergence; Lorentz force is induced due to field interaction; not explicitly explained]</td>
<td>(b) This template strand and this template strand are exposed. So the bases are now exposed. So what happens? The DNA nucleotides will fit in, the free nucleotides will now base-pair, so they will base-pair. The G-nucleotide, the T-nucleotide will base-pair, just like that. [self-organization]</td>
</tr>
<tr>
<td>(c) The lipid molecule has polar and non-polar ends. The polar end faces the aqueous and the non-polar end faces inside with other non-polar ends. [self-organization; did not emphasize the spontaneity of arrangement]</td>
<td>(c) This molecule has a polar head and non-polar tails, a polar head and two non-polar tails right? As a result of this, yes, it will orientate. the key word, it will self-orientate in such a way that the polar head is facing … where? The aqueous medium right? If they orientate in that way, what will they form? A bilayer structure, right? [emergence and self-organization]</td>
</tr>
<tr>
<td><strong>Signposts</strong></td>
<td><strong>Signposts</strong></td>
</tr>
<tr>
<td>Teaching a concept or topic with an implicit reference to systemic patterns arising from localized behaviors and the non-intentionality or spontaneity of the localized behaviors.</td>
<td>[i]: big changes from localized effects, emerges, implies systemic phenomena occurring as a result, leads to, causes … in turn causes…, A → B → C</td>
</tr>
<tr>
<td>[ii]: non-intentional, spontaneous, it “just happens”, “by itself,” “self-orientate”</td>
<td></td>
</tr>
</tbody>
</table>
Section D: Decentralization
Description: The focus is how the system obtains its order – centralized (by certain authority or controlling body), or decentralized (no single leader).

0: Not implied/observed
Idea of decentralization is not observed nor implied in teaching episodes or written descriptions.

1: implied and 2: explicitly described or explained
Teaching episodes or written descriptions implying (1) or explicitly describing or explaining (2) idea of decentralization: the system is affected by more than 2 components and not just one central cause or agent.

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<th>I: implied</th>
<th>2: explicitly described or explained</th>
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<td><strong>Exemplars</strong></td>
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<td>(a) if one of the light bulbs was to break, say bulb number 3 was to break, what would happen to the ammeter reading here, and the brightness of the remaining bulbs? Now, how does the current flow? Let's use this first method. How does the current flow? If I call this $I_1$ [main current from cell], and I call this $I_2$, $I_3$, $I_4$, the current through the first, second, third bulb. What is the relation that you can use to link up the current? <em>decentralization; but not explicit in saying all the bulbs contribute to the overall current</em></td>
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<td>(b) how do we explain acidity for phenol? We look at the acidity of the phenoxide. So if I have a phenol that is substituted, we also look at the stability of the phenoxide, the substituted phenoxide. We have a NO$_2$ here, here, we have an alkano group here. So is the negative charge more or less dispersed compared to a normal phenoxide? The one with a more dispersed negative charge here, the less or more acidity? <em>decentralization in terms of explaining acidity of phenol; but not explicit that there are several factors to consider</em></td>
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<td>Teaching a concept or topic with an implicit reference to the multiple factors or causes related to the process or phenomenon.</td>
<td>Many factors or components involve in the scientific process or phenomenon.</td>
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<td>The various factors or components can affect the outcomes of the process or phenomenon.</td>
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BIBLIOGRAPHY


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