2016

Education in the Age of Complexity: Building Systems Literacy

Caitlin S. Steele
University of Vermont

EDUCATION IN THE AGE OF COMPLEXITY: BUILDING SYSTEMS LITERACY

A Dissertation Presented

by

Caitlin S. Steele

to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
Specializing in Educational Leadership and Policy Studies

May 2016

Defense Date: March 30, 2016
Dissertation Examination Committee:

Alan Tinkler, Ph.D., Advisor
M.D. Usher, Ph.D., Chairperson
Maureen Neumann, Ph.D.
Cindy Gerstl-Pepin, Ph.D.
Cynthia J. Forehand, Ph.D., Dean of the Graduate College

Abstract

In the 21st century, transdisciplinary approaches to research and problem solving rooted in complexity theory and complex systems methodologies offer hope for understanding and solving previously intractable problems. However, in the face of daunting modern challenges like a broken health care system, growing social and economic inequity, and climate change, the knowledge and skills required to understand and ultimately solve problems across interdependent complex systems are distinctly lacking in our collective practice.

The underlying premise of this study is that if modern society is to deal effectively with interconnected challenges across ecological, social, political, and economic systems, our education system must prepare students to grapple with complexity. This research expands upon previously identified core complex systems knowledge, skills, and dispositions to contribute rich description to a working definition of the term *systems literacy*, develop a theory of how one becomes *systems literate*, and offer access points for educators entering the world of complexity.

The study employed complexity-informed grounded theory methods including data from semi-structured interviews with complex systems scholars and educators across a wide range of academic disciplines. Additional data was gleaned from texts and online resources produced by systems educators and complexity scholars.

The three resulting journal articles were designed to consolidate much of what is known about complex systems into a package that is useful for educators, school leaders, and other stakeholders. Together, these articles contribute to an understanding of how curricula and instruction might better emphasize the dynamic nature of interdependent complex systems and the agency of individuals and collectives to innovate, engage in authentic problem solving, and participate in actively preserving and reshaping the world in which we live.

Dedication

To my children, Daniel and Una Steele.

Acknowledgments

Many thanks to my gracious interviewees who generously shared the time, energy, ideas, and feedback that made this study possible.

Thank you also to Maureen Neumann for her ongoing support and critical feedback throughout this extended study, to Judith Aiken for offering structure to what otherwise would have been an overwhelming process, and to Alan Tinkler for his enthusiastic advising throughout my four years at the University of Vermont.

Thank you to the other members of my dissertation committee, Cindy Gerstl-Pepin and Mark Usher, for their valued feedback and support; to my two most consistent peer readers, Lisa Natkin and Patience Whitworth; and to the other faculty and students in UVM's doctoral programs in education. It is wonderful to be a part of a dynamic learning community.

Finally, and most importantly, thank you to my husband Tim Steele and to my parents Larry and Leslie Shipps, without whom I could not have done this.

Table of Contents

Page

Citations …..……………………………………………………………………….. ii

Dedication ……………………………………………………………………….. ii

Acknowledgments ……….……………….…………………………...……... iii

List of Tables ……...……………………………………………………..……... x

List of Figures …………………………………………………………..…..…... xi

Chapter 1: Education in the Age of Complexity ………………..……………...….. 1

1.1. Introduction…………………………………………………...…...… 1

1.2. Complexity: The Basics ….……………………………………..…..…..... 3

1.3.The Age of Complexity and the Character of Modern Problems…..……….…...... 7

1.4. School Reform Rooted in the Linear Paradigm ………………………...…….. 10

1.5. Statement of the Problem……………………………………….……............. 12

1.6. Research Questions…………………………………………………….…..... 14

1.7. Significance of the Study …...………...………….……….................................. 15

1.8. Organization of the Study…………………………………………................. 16

Chapter 2: Review of Literature ……………………...…………………..………… 14

2.1. Introduction ..…………………………………………………………... 14

2.2. Systems in Education ……………...…………………………………... 15

2.2.1. Systems education in theory …….…………………………………… 15
2.2.2. Systems education in practice ……………….……………….................. 17
2.2.3. Systems in mainstream education …...……………………………….... 18

2.3. Conceptualizing Systems Literacy ……………………………………….. 19
2.3.1. Overview ……………………………………………………………… 19
2.3.2. Pieces of the literacy puzzle ……………..………………….................. 20
2.3.3. The history and canon of complexity ……………………..……............. 25

2.4. Becoming Systems Literate ………………………...…………………….. 26

2.5. The Purpose of Systems Literacy ……………………….……..……... 29

Chapter 3: Research Methods ...…………………………………...…….....… 32

3.1. Overview ……………………………………………...………………….. 32

3.2. Conceptual Framework: *Literacy in 3D* ………... 32

3.3. Theoretical Framework: The Complexity Frame of Reference ……….…….... 34

3.4. Grounded Theory …………………..……………………………………….. 35
3.4.1. Theory ………………………………………………………………..….. 36
3.4.2. Concepts, categories, properties, and dimensions …………….……….... 37
3.4.3. Theoretical sampling for comparative analysis ………………….……..... 37
3.4.4. Coding ………………………………………………………………… 38
3.4.5. Memoing toward saturation ……………………………….................. 39

3.5. Grounded Theory and Systems Literacy ………………………….………… 40
3.5.1. Topical fit ……………………………………………………….………… 40
3.5.2. Theoretical fit …………………………………...…….….………… 41

3.6. Research Design ………………………………………………………….. 43
3.6.1. Sampling …………………………………………………….……………... 44
3.6.2. Participants ……………………………………………………..………... 44
3.6.3. Setting, access, and ethical considerations ………………...………….. 46

3.7. Three Phases of Research ... 47
3.7.1. Phase one ... 47
3.7.2. Phase two ... 48
3.7.3. Phase three, the dissertation ... 49
3.7.4. Defining systems literacy ... 50
3.7.5. Becoming systems literate ... 52
3.8. Limitations and Delimitations ... 54
3.9. Background and Role of the Researcher ... 55
3.10. Validity of Interpretation ... 57
3.11. Results, Interpretations, and Implications ... 60
Chapter 4: Three Journal Articles ... 61
Systems literacy in three dimensions: Cultural, operational, and critical competencies for living in a complex world ... 61
Abstract ... 61
Education in the Age of Complexity ... 61
Systems Education ... 62
Conceptual Framework: The 3D Model ... 63
Research Design ... 64
Defining Systems Literacy ... 67
The Cultural Dimension ... 67
The Operational Dimension ... 70
The Critical Dimension ... 73
Summary ... 76
The Purpose of a Systems Education ... 77
Note ... 78

References 78

Becoming Systems Literate 82

Abstract 82

Introduction 82

Systems Literacy 83

Systems Literacy Across Three Dimensions 84

Systems Literacy Defined 84

The Cultural Dimension 85

The Operational Dimension 85

The Critical Dimension 86

Research Design 87

Data Sources and Methods 88

Credibility of Findings 89

Becoming Systems Literate 90

Grounding 90

G1. Grounding in Natural and Manmade Systems 90

G2. Grounding in Real World Problems 91

G3. Grounding in One or More Disciplines 92

Questioning 92

Q1. Asking Big Questions 92

Q2. Questioning Methodologies, Ontologies, Mental Models, and Personal Biases 93

Q3. Questioning Identities and Social Structures 94

Q4. Embracing Uncertainty and Ambiguity 94

Broadening 95

B1. Broadening Through Formal Education 95

B2. Broadening Beyond Formal Education 95

Integrating 96

I1. Integrating Knowledge Across Fields and Experiences 96

I2. Integrating Through Tension 97
I3. Integrating Through Narrative 97
I4. Learning, Integrating, Adapting, and Evolving 98
Developing a Systems Lens 98
D1. Learning the Culture of Complexity 98
D2. Developing a Systems Lens Through Formal and Informal Education 99
D3. Refining the Systems Lens Through Modeling and Experimentation 99
Discussion 101
Systems Literacy in K-16 Education 102
References 103
Photomosaic Possibilities: Developing a Systems Lens to Inform Education Redesign 107
Abstract 107
1. Introduction—A call for systems literate citizens 107
2. A grounded theory study of systems literacy for K-12 education 108
2.1. Research design 109
2.2. Defining systems literacy 109
2.3. Becoming systems literate 110
3. Implications 112
4. Changing the way educators see the world 113
4.1. Photomosaic possibilities for innovation in educational design 114
4.2. Learning together 115
4.3. Focusing on complexity 116
4.4. Professional development and the five processes of becoming systems literate 117

6. Conclusion …………………………………………………………………………. 117

References …………………………………………………………………………….. 118

Chapter 5: Implications and Conclusion ...………………..……………….....…...... 124

5.1. Living in a New Age …………………………….....………...…………..….. 124

5.2. Arriving at Complexity ……………………………………………………..…… 126

5.3. Findings in Brief ………………………………………………………….….. 129

5.3.1. Systems literacy—a working definition …………………………….. 129

5.3.2. Becoming systems literate—a theory in progress …………………... 131

5.4. Implications—Intervening at Points of High Leverage ……………………… 133

6. COMPREHENSIVE BIBLIOGRAPHY ………………………….……..………… 136

7. APPENDICES …………………………………………………..………………..… 151

7.1. IRB Forms ………………………………………………………………….... 151

7.2. Systems Skills Inventory …………………………………………………….. 152

7.3. Phase Two—Interview Protocol …………………………...……………….... 157

7.4. Phase Three—Interview Protocol ………………………………………….… 158

List of Tables

Table Page

Chapter 2: Review of Literature

Table 2.1: Systems Knowledge, Skills, and Dispositions ………………….………….. 26

Chapter 3: Research Methods

Table 3.1: Participants ……………………………………..………….……….……. 45

Table 3.2: Text-Based Data Sources for Defining Systems Literacy …….….….….… 51

Table 3.3: Texts Analyzed as Data Sources for Becoming Systems Literate ……..…… 53

Table 3.4: Data Collection and Member-Checking ………………………..…………… 59

Chapter 4: Three Journal Articles

Article 1

Table 1: Text-Based Data Sources …………………………..………….…………… 65

Table 2: Participants …………………………..……….………………….………… 66

Table 3: Components of Systems Literacy ………………………….…….………… 68

Article 2

Table 1: Three Components of the Cultural Dimension of Systems Literacy ………..… 85

Table 2: Four Components of the Operational Dimension of Systems Literacy ……..… 86

Table 3: Three Components of the Critical Dimension of Systems Literacy ……..…… 87

Table 4: Participants ……………………………………..…………..……………. 89

Table 5: Components of Systems Literacy Aligned with Processes of Becoming …… 100

Appendices

Table 7.3.1: IRB Documents ...…………………..…………………….…….…..…… 151

Table 7.2: Phase Two Interview Protocol ...……………………..…………….……….. 157

Table 7.3: Phase Three Interview Protocol ...……………………..……..….………… 158

List of Figures

Chapter 3: Research Methods

Figure 3.1. Research as an iterative process …………………..……………………….. 43

Chapter 4: Journal Articles

Article 1

Figure 1: Interconnected dimensions of systems literacy ...……………..………..…… 74

Article 2

Figure 1: Common themes in becoming systems literate ..……………..……………… 90

Figure 2: Simultaneous and overlapping cycles of becoming ..……………...…….. 102

Chapter 1: Education in the Age of Complexity

> The widening gap between schools' aims and what will be needed of tomorrow's globally oriented, socially responsible knowledge workers has become the biggest unrecognized threat to America's future. (Senge, 2012, p. 45)

1.1. Introduction

It has become popular to describe our education system as a machine-like product of the Industrial Age (Banathy, 1991; Cassell & Nelson, 2010; Cunningham, 2014; Robinson, 2010; Senge, 2012). Characterized by blocks of time, bell schedules, credits attached to seat time, learning attached to grades, schools can act as knowledge factories producing the workers needed to keep our country and economy chugging along. While our education system has been a stabilizing factor in American history and has contributed to and perpetuated democratic ideals (Friedman, 2002), it has also been a powerful force for maintaining the status quo (Anyon, 1980; Banathy & Rowland, 2004; Betts, 1992). Increasingly, it is becoming clear that the status quo is no longer sustainable (Nijs, 2015; Rockström et al., 2009). In an age of growing inequity, racial tension, political inaction, international conflict, environmental destruction, and climate change, inasmuch as our education system serves to reproduce established norms, it runs the risk of exacerbating complex problems like these (Wessels, 2006). In changing times, education must evolve.

Many authors have made the case for approaching school change through the logic of complex adaptive systems (e.g., Banathy, 1991; Cunningham, 2014; Marshall, 2006; O'Day, 2002; Senge, 2000; Snyder, 2013). The idea of education as a complex system is well developed in the literature on organizational theory and school change (Banathy, 1991; Morgan, 2006; O'Day, 2002; Senge, 2010; Snyder, 2013). For this dissertation, I agree that there is much to be gained by applying complexity theories to educational change efforts, but rather than focusing on *how schools work,* my research emphasizes the question, *To what end?*, and I argue that in changing times, we must reconsider the purpose and goals of an education system nested within and evolving along with other social, political, economic, and environmental systems.

The premise of this study is that if modern society is to deal effectively with interconnected challenges across ecological, social, political, and economic systems, our education system must prepare students to grapple with complexity. We must prepare *systems literate* global citizens, students (and teachers) who understand the fundamentals of complex systems across disciplinary boundaries and identify themselves as active agents in the evolution of their world.

1.2. Complexity: The Basics

Before launching into the details of the study, it will be useful to introduce several key concepts underlying complexity studies. A *system* is a group of parts that together constitute a cohesive whole (see, e.g., Ackoff, 1997; Wessels, 2006). That whole may be a toaster, a cat, a community, or an ecosystem. Systems exist at every scale. They can be linear or complex. In a *linear system*, the parts interact in a predictable fashion (Wessels, 2006). Most machines are linear systems. Wessels offered the example of a clock. The hands and face and gears, the exterior along with all of the inner workings, together constitute a system. Assuming the clock has power, it should predictably keep time. A clock can break, but it cannot adapt. It cannot *self-organize.* It does not take in energy to grow or information to learn. It does not become increasingly complex over time. It does not feed back on itself. These are key characteristics that distinguish a linear system from a complex one.

A *complex system*, like a linear system, is a collection of smaller parts which together function as a cohesive whole. Complex systems can be biological (e.g., the human body), ecological (e.g., a coral reef), or manmade (e.g., a community, an organization, a political system, an economy). They are typically characterized by networked connections of interdependent agents organized without central control (Mitchell, 2009). They are dynamic and adaptive. They evolve.

The self-organizing ability of complex systems results in *emergent properties*, elements of a system that could not be predicted by studying the parts in isolation (Manson, 2001; Wessels, 2006). Termite colonies acting as super-organisms exhibit emergence; creativity, love, and compassion are emergent properties of the human brain (Wessels, 2006). Self-organization and emergence are possible because of *feedback*, which can come in the form of energy or information. *Negative feedback*, sometimes called *self-regulating feedback*, maintains a system's status quo (as in a thermostat regulating indoor temperature). *Positive feedback*, or *reinforcing feedback*, pushes a system in a particular direction. It "amplifies the system's behavior in a directional, accumulative way" (p. 16). Positive feedback is what we worry about in the context of climate change. It is what we point toward in examples like the melting Arctic sea ice. Dark seawater, as opposed to bright sea ice, absorbs more heat from the sun, speeding up the warming (Poppick, 2011). Positive feedback accumulates and can lead to *bifurcation,* "rapid, large-scale change in a complex system's behavior" (Wessels, 2006, p. 119). In the case of climate, rapid, large-scale change could be devastating. In social systems, it can mean revolution. In many examples like these, common concepts from complexity studies transfer across contexts and disciplines.

Over the past several decades, people have developed a range of methods for understanding and impacting the myriad complex systems that make up our world. A popular approach, *systems thinking,* delineates a specific set of critical thinking skills for grappling with complexity. Primarily descriptive in nature, systems thinking techniques have been applied in business strategy (Senge, 2008), organizational theory (Ackoff, 1997; Morgan, 2006), and interdisciplinary problem solving (Bar-Yam et al., 2004; Meadows, 1999). *System dynamics*, like *network analysis* and *agent-based modeling*, is a particular type of modeling rooted in systems theory. System dynamics is particularly relevant in the context of K-12 education because a vibrant community of scholars and practitioners (many affiliated with the Waters Foundation and the Creative Learning Exchange) have been working on bringing systems thinking and system dynamics concepts to K-12 education for decades (Fisher, 2011; Sweeney & Sterman, 2007). *Complex systems science*, with roots in *chaos theory* (Wessels, 2006), is a scientific perspective that has emerged since the mid-twentieth century. While the term *complex systems* refers to the natural and manmade systems themselves, it is also an overarching name for a series of modern computational approaches to studying those systems.

It is important to note that there is not one accepted definition of complexity or version of complexity theory (Geert & Steenbeek, 2014; Mitchell, 2009; Umphrey, 2002). Manson (2001) divided complexity into three separate branches: *algorithmic complexity* (rooted in information theory and mathematical complexity), *deterministic* *complexity* (connected to chaos and catastrophe theories), and *aggregate complexity* (aligning most closely with systems thinking and system dynamics branches of complexity studies). Byrne and Callaghan (2014) distinguished between *restricted complexity* and *general complexity* and coined the term *complexity frame of reference* to describe a particular ontological approach to the world, a way of "understanding the social world and the intersections of that social world with the natural world within which it is embedded" (p. 44). In this study, the word *complexity* is employed generally and refers to a recognition of the interconnectedness and interdependence of systems at multiple scales and an attempt to account for the dynamic, non-linear nature of the world around us.

Grappling with complexity requires *interdisciplinary understanding*, which Marshall (2006) defined as "the ability to think deeply in two or more disciplines." Interdisciplinarity, she wrote, "enables learners to look across, between, and within disciplinary boundaries and 'soften' them so they can fluidly connect their concepts, symbol systems, forms of knowledge representation, and modes of inquiry" (p. 53). Because complex systems are ubiquitous, they serve as a powerful interdisciplinary theme. But complexity as a concept is more than interdisciplinary; it is *transdisciplinary.*

> Transdisciplinary understanding goes even deeper and further by embracing all the ways we come to know: knowing through disciplines, knowing across and between them, and, most important, knowing beyond disciplinary boundaries. The purpose of transdisciplinary learning is to understand the unity of knowledge by identifying principles and patterns that go beyond a single domain and are common to all of them. (Marshall, 2006, p. 57)

Complexity is, by its nature, *transdisciplinary*, or perhaps, as Byrne and Callaghan (2014) described it, *post-disciplinary*.

1.3. The Age of Complexity and the Character of Modern Problems

If the machine metaphor for schools is a product of the industrial paradigm, the complex systems metaphor is an emergent property of a new paradigm that has taken shape beyond our school walls (Ackoff, 1997; Alperovitz, Speth, & Guinan, 2015; Conklin, 2009; Dias, 2015; Doll, 1989; Forrester, 2007; Marshall, 2006; Meadows, 1999; Mitchell, 2009; Wessels, 2006). Since the mid-twentieth century, systems thinking, system dynamics, and complex systems sciences—diverse but related modes of inquiry—have offered new mindsets and methods for studying the world and thus new possibilities for addressing old problems (see, e.g., Doll, 1989). Scholars and professionals in scientific fields ranging from biology and ecology to physics, math, and engineering have explored complexity in their respective disciplines, and over time, the boundaries of those disciplines, once so distinct, have started to blur (Ackoff, 1997; Forrester, 2007; Mitchell, 2009; Montuori, 2015a). In the humanities and social sciences, the modern explosion of big data and the computational capacity of personal computers have provided access for researchers to tackle quantitative aspects of questions they could answer only theoretically in times past (Ackoff, 1997; Byrne, 2014; Goerner, 2015; Wessels, 2006). Non-quantitatively, scholars have drawn parallels between complexity and the postmodern perspective (Cilliers, 1998; Dias, 2015; Toscano, 2006).

Through more than 60 years of inquiry into complexity, scholars and practitioners have developed deep understandings of the interdependent complex systems that constitute our world. Knowledge of the structures and dynamics of biological and ecological systems have come to inform our understandings of how manmade systems—political, socio-technical, economic, even linguistic systems—work, interact, and change over time (Bar-Yam, Ramalingam, Burlingame, & Ogata, 2004; Meadows & Wright, 2008; Mitchell, 2009). The modern concept of complexity, with roots in a range of disparate fields of study, recognizes in all domains the interconnectedness and interdependence of systems and subsystems. Core concepts of self-organization and emergence have become central to real-world problem solving as systems theorists have come to recognize the nestedness of individuals within society and to quantify and explain the dependence and impact of society on the natural world (see, e.g., Meadows & Wright, 2008; Senge, 2012). This represents a distinct paradigm shift, a transition from an industrial to a post-industrial age.

Describing this paradigm shift, Conklin (2009) referred to the recent past as the Age of Science and explained,

> In the Age of Science, the job of Science was to describe the universe. Once we had created a good description of the natural world, we could begin to exercise control, and the path was opened for technology—the art of harnessing, controlling and transforming our world. (p. 17)

In what Conklin called the Age of Design (which this study refers to as the Age of Complexity), he argued, the focus has shifted from *harnessing and controlling* to *creating*. The skills that were important before remain relevant, but they no longer suffice. In the face of complexity, he said, it has become clear, "the notion of business-as-usual that we inherited from the industrial era is a manufacturing-based, linear process-oriented approach, and if you are locked into that view, you will miss out on all the deeper problems" (p. 20).

Systems theorists have characterized these deeper problems in a number of ways. Ackoff (1997) and Denning (2007) identified complex problems as *systems messes*. Others have called them *wicked problems* (Churchman, 1967 cited in Byrne, 2014; Conklin, 2009; Denning, 2007). Still others have referred to them as *21st century problems* (Rogers, Pfaff, Hamilton, & Erkan, 2013). Whatever name they have given them, systems theorists have recognized modern challenges as complex, characterized by competition for limited resources, interdependence among multiple players, and complications associated with conflicting priorities and needs. Such challenges exist at the intersections of local and global societies, ecosystems and "anthropo-systems"; they exist across space-scales—"from the local to the planetary"—and time-scales—"from the short to the very long term" (Kagan, 2010, p. 1094). Alperovitz, Speth, and Guinan (2015) argued that in cobbling together solutions to modern challenges, we too often "draw upon the very same institutional arrangements and practices that gave rise to the problems in the first place" (p. 7). Such business-as-usual solutions not only fail to solve persistent problems, but often make them worse (Sterman, 2002, p. 501).

Dubberly (2014) discussed modern leaders' inability to design effective solutions to such problems:

> Decision makers "not knowing what they are doing," lacking "adequate basis to judge effects," is not stupidity. It's a type of illiteracy. It is a symptom that *something* [emphasis added] is missing in public discourse, in organizations and businesses, and in our schools. (p. 2)

That *something* is a deep understanding of complex systems. Dubberly explained that most of our important challenges are rooted in such systems. He named “energy and global warming; water, food, and population; health and social justice,” but he explained that “in the day-to-day world of business, new products that create high value almost all involve systems, too” (p. 2). Today’s problems, from increasing economic inequity to global climate change, but also today’s greatest innovations, are products of complexity. Wessels (2006) argued that if we hope to find effective answers to challenging questions around sustainability and authentic human progress, we must understand the natural laws governing complex systems. If we hope to solve these problems at scale, we are going to need to develop a systems literate society (Dubberly, 2014; Sweeney, 2014). Our education system has an important role to play in this work (Apple, 2008; Cassell & Nelson, 2010; Edelstein, 2011).

1.4. Statement of the Problem

Several authors have written about the reductionist approach to curriculum that characterizes our current K-12 education system (e.g. Betts, 1992; Fisher, 2011; Wessels, 2006). In this outdated model, knowledge is fragmented and compartmentalized (Banathy & Rowland, 2004; Fisher, 2011; Marshall, 2006; Richmond, 2013; Sweeney & Sterman, 2007). English, math, science, and social studies are taught as distinct subjects. The arts, physical education, and foreign languages are secondary, often elective lines of study. Content is taught in preparation for assessments. Learning is seen as preparation for college or careers. Practical application of knowledge is too often relegated to vocational fields, often taught on alternative campuses. Schooling can appear to a student to be little more than a series of seats to sit in on one’s way to whatever is next.

Despite many efforts at modernizing education, the typical K-12 curriculum does not reflect the modern complexity paradigm.

As Sweeney (2009) argued, "Most of us were not taught in school to 'think about systems.' Traditional schooling has tended to separate the material world from the social world, reinforcing the notion that knowledge is made up of many unrelated parts" (n.p.). These old, entrenched curricular patterns can be problematic in a number of ways. In math, a student with a talent for plugging the right numbers into the right formulas may excel and still graduate from high school without any concept of the power of mathematics to model the world (Lockhart, 2008). We can and do test kids on reading comprehension, grammar and mechanics, and literary terminology, but those testable elements rarely point to the role literature has played in conveying, predicting, and shaping the state of the world around us, the creative power of language in the human experience. In science, we teach geology, biology, chemistry; a lucky few get ecology and physics. But how often do we challenge students with questions at the intersections of those fields? Do our tests address what it means to be scientifically literate in general or what role such literacy (or illiteracy) plays in personal and collective decision making? Likewise, textbook history too often teaches a finished tale, highlighting (from a dominant perspective) times of change in the past while propagating an implicit belief that the present is relatively static.

Our education system teaches facts and details well. Harder to test, but no less important are questions about what it means to be an engaged and effective citizen in changing times. Sweeney and Sterman (2007) argued,

> While the world around them grows increasingly complex and interdependent, schools continue to fragment and compartmentalize, reinforcing the notion that knowledge is made up of many unrelated parts and providing little opportunity for students to see recurring patterns of behavior across subjects and disciplines. (n.p.)

Such a linear, fragmented curricular model by its nature fails to illuminate the intersections between science and literature, math, history, politics, or art (Bennett & Sweeney, n.d.; Fisher, 2011; Sterman, 2002; Sung et al, 2003). Implicitly left out in an effort to teach testable content are a sense of connection (content to content, content to place, school to world) and a concept of knowledge as evolving and in process. Teaching connections like these explicitly and supporting students in developing the skills to make such connections on their own will be central to updating the traditional curriculum for the modern era. To thrive in the Age of Complexity, students need to develop systems literacies.

1.5. Research Questions

By exploring common concepts and themes that have emerged through the work and ideas of complexity scholars and systems educators, this study builds upon a working definition of the term *systems literacy* and offers a grounded theory of *how one becomes systems literate.* Thus two research questions guided this work.

1. What is systems literacy?
2. How does one become systems literate?

The first question aimed at building upon current knowledge and contributing rich description to the concept of systems literacy. The second focused inquiry toward developing a theory of the process of becoming systems literate. Both are answered with K-12 educators in mind. The three resulting journal articles are rooted in the assumption that, if educators are to support students in developing systems literacy, they first need to develop a systems lens themselves.

1.6. Significance of the Study

In his World War II era poem *The Age of Anxiety*, Auden (1947) grappled with the implications of a dehumanizing industrial paradigm, writing, "But the new barbarian is no uncouth/Desert-dweller; he does not emerge/From fir forests; factories bred him;/Corporate companies, college towns/Mothered his mind, and many journals/Backed his beliefs" (p. 16; discussed in Jacobs, 2012). More than a half century later, Marshall (2006) described the current transition into a post-industrial paradigm: "Our cultural mind is slowly shifting from fragmentation and reductionism, expressed in excessive competition, unbridled acquisition, winning, short-term thinking, and isolated self-interest, to integration and interdependence—collaboration, shared purpose, and global sustainability" (p. 179). This is the paradigm of the Age of Complexity.

In the Age of Complexity, scientists, scholars, and practitioners work across traditional disciplinary boundaries applying well-developed theories and methods to understand, describe, and impact interconnected systems in the world around them. With increasingly sophisticated understandings of complexity, they work toward solving what a generation ago would have been impossible problems. There are many examples of *systems literate* individuals in our society. Our education system has a role to play in developing this modern mindset and the skills associated with it in society as a whole.

To that end, this study has consolidated much of what is already known about complex systems into a package to be useful to educators, school leaders, and others with pedagogical expertise. In doing so, it makes a concrete contribution to the conversation about how our education system might better emphasize the dynamic nature of the world in which we live and the agency of individuals and collectives in innovation and authentic problem solving. And it presents the concept of *systems literacy* as an access point for educators entering the world of complexity.

1.7. Organization of the Study

This first chapter has set the context for this study on *systems literacy,* including a basic historical and theoretical introduction to complexity. Chapter two discusses the relevant literature opening with complexity in the current curriculum and curricular reform efforts. It discusses systems thinking and system dynamics work in K-12 education and outlines a working definition of systems literacy based on previous literature. Chapter three describes the grounded theory methodology that informed data collection and analysis procedures. Chapter four presents the study's findings and some implications for those findings in the form of three journal articles. The first provides an updated definition of systems literacy. The second describes common patterns in the development of systems literacy. The third argues that developing a systems lens among teachers and school leaders will be a key leverage point in shifting the education system as a whole to support students in becoming systems literate citizens. The final chapter summarizes and reflects on the study's findings and interpretations, reemphasizing the potential for systems literacy to provide learners with knowledge, skills, and dispositions to access and affect the Age of Complexity.

Chapter 2: Review of Literature

2.1. Introduction

Having established the context for a discussion of education and systems literacy in chapter one, this second chapter opens with a review of the literature arguing for a curriculum more conducive to developing students' systems skills and knowledge, the competencies required for solving complex problems in the Age of Complexity. It outlines first ways in which the new complexity paradigm has already impacted the field of education discussing systems education in theory and in practice along with mainstream curriculum trends influenced less directly by the complexity paradigm. These include the standards movement (including explicit and implicit references to complexity and systems in the *Common Core State Standards*, the *Next Generation Science Standards*, and the *C3 Framework for Social Studies*), 21^{st} century skills, and educating for sustainability, among others. The purpose of this section is not to discuss any one of these documents or efforts at length, but rather to show connections between them and to demonstrate how viewing curricular reform through the lens of systems literacy could lend a sense of shared purpose to disparate groups of educational change agents.

The next section introduces authors and organizations that have outlined skills associated with systems thinking and projects designed to teach both theoretical and computational aspects of complex systems. This section makes the case that several groups have engaged in the work of delivering systems skills to students and that—though what is emphasized varies from one context to the next—all of this might fit well under the umbrella of *systems literacy.* A few authors, discussed here, have begun the work of defining this relatively new term, and this section closes by making the case that extending their work—further developing the working definition of systems literacy—represented a valuable opportunity to advance the concept and contribute to the literature. In order to establish the context for an exploration of how one becomes systems literate, one more literature review section synthesizes ideas from authors who have written about their personal paths into complexity studies. The chapter concludes with a discussion of the implications of systems literacy, compiling several authors' hopes and predictions for systems education.

2.2. Systems in Education

2.2.1. Systems education in theory. Various authors have promoted the idea of rethinking the curriculum (at levels ranging from preschool to graduate school) through a systems lens (e.g. Betts, 1992; Cassell & Nelson, 2010; Forrester, 2009; Grauwin, et al., 2012; Metz, 2012; Senge, 2012; Sung et al., 2003; Sweeney, 2014). Metz (2012) argued, "It's crucial that students learn the habits of systems thinkers in order to solve our most intractable problems – poverty, hunger, war, ignorance, resource depletion, and environmental degradation, among many others" (n.p.). Forester (2007) claimed, "It is time to start working toward an integrated educational process based on an understanding of systems that is more effective, more appropriate to a world of increasing complexity, and more compatible with unity in life" (p. 356). Senge (2012) advocated for systems thinking and learner centered pedagogy as core elements of sustainability education. "Education for sustainability," he explained, "is more than just a new curriculum. It is about how the content and process of education can be interwoven with *real-life contexts* to create opportunities for young people to lead in building sustainable communities and societies" (p. 47).

Forrester (2009) and other authors (e.g. Fisher, 2011; Plate & Monroe, 2014; Sweeney & Sterman, 2000, 2007) have advocated not only for systems thinking in the curriculum but for system dynamics as well. Forrester (2007) described systems thinking as a “sensitizer” but argued that it is only through modeling systems and simulating situations that “inconsistencies within our mental models are revealed. Systems thinking,” he claimed, “can be a first step toward a dynamic understanding of complex problems, but it is far from sufficient” (p. 355). He believed that system dynamics modeling should be taught in schools not as a subject in itself but “as a common thread running through all subjects” (p. 354).

Sweeney and Sterman (2000) developed methods for assessing systems thinking and system dynamics skills, focusing in particular on basic comprehension of stocks and flows. The subjects of their study were graduate students with strong math/science backgrounds. Though all subjects had studied calculus, most failed to perform well on assigned tasks involving basic calculus concepts and elementary calculation but also an understanding of key “elements of dynamic complexity” (p. 283). Their findings pointed toward limited problem-solving abilities in complex real world scenarios. Plate and Monroe (2014) developed a series of rubrics to assess systems skills at basic, intermediate, and advanced levels of literacy. Organizations like the Waters Foundation and the Creative Learning Exchange have made the case that filling these gaps in the problem-solving abilities of highly educated individuals must start at the K-12 levels (Creative Learning Exchange, 2016; Waters Foundation, 2016).

2.2.2. Systems education in practice. According to Sweeney (2009), over the past two decades

> a growing number of schools in the U.S. and worldwide have begun in earnest to teach students to think about systems—rather than fragments—as the context for exploring complex problems, and for fostering more intentional decision making about the natural world. (n.p.)

Fisher (2011) described herself as "part of a relatively large group of teachers across the country in grades from K through 12, in many disciplines, who have applied systems thinking in the classroom" (p. 395). Both of these authors have collaborated with the Creative Learning Exchange, an organization based out of Cambridge, Massachusetts that exists to support the development of systems thinking and system dynamics skills in K-12 schools (Creative Learning Exchange, 2016). The Waters Foundation is a similar organization based out of Pittsburgh, Pennsylvania (Waters Foundation, 2016). "The mission of the [Waters Foundation's] Systems Thinking in Schools Project is to increase the capacity of educators to deliver academic and lifetime benefits to students through the effective application of systems thinking concepts, habits and tools in classroom instruction and school improvement" (Waters Foundation, n.d., p. 1). Both organizations offer professional development opportunities, curriculum resources, and support to educators and schools. Scholars associated with each have published papers, articles, and other works promoting the work of schools incorporating these ideas into the curriculum.

A Waters Foundation (n.d.) review cataloged qualitative and quantitative studies assessing the efficacy of its programs and made a case for scaling up the organization's efforts. In the context of a meta-analysis of existing research, the authors presented five key findings arguing that systems thinking helps students by (1) Making their thinking visible, especially through the use of diagrams, graphs and other visual aids; (2) Making connections across disciplines and between school and students' life experiences; (3) Improving students' abilities to solve problems by accessing varied perspectives, challenging "obvious solutions," considering systems archetypes (common patterns of behavior), and understanding their own mental models; (4) Developing reading and writing skills; and (5) Increasing engagement (p. 6-7).

The Santa Fe Institute is a complex systems research institution rooted in the computational branches of complexity. In collaboration with the Massachusetts Institute of Technology, the National Science Foundation, and various local partners including businesses, schools, and science centers, the Santa Fe Institute has hosted a program for middle school students called Project GUTS. GUTS stands for Growing Up Thinking Scientifically, which the program website defines as "learning to look at the world and ask questions, develop answers to the questions through scientific inquiry, and design solutions to their problems" (Project GUTS; Santa Fe Institute, 2016). In addition to scientific inquiry, the program emphasizes complex systems concepts and computer modeling and simulation, and though the program description does not use the term *systems literacy,* this computational approach to systems must also inform a working definition of that term.

2.2.3. Systems in mainstream education. Systems thinking, systems modeling, and related transdisciplinary topics have made their way into state and national curriculum guidelines including the *Common Core State Standards*, the *Next Generation Science Standards*, and the *C3 Framework for Social Studies* (National Council for the

Social Studies, 2013; National Governors Associate for Best Practices, 2010; NGSS Lead States, 2013; Plate & Monroe, 2014; Sweeney & Sterman, 2007; Waters Foundation, n.d.). In the latter, they are especially prevalent within the "seven crosscutting concepts that bridge disciplinary boundaries, uniting ideas throughout the fields of science and engineering" (NGSS Lead States, 2013, p. 1). Of those seven concepts, four name "systems" directly. The other three outline what are inarguably systems-related skills and ideas (e.g., observing patterns, investigating multifaceted causal relationships, etc.). The purpose of each "is to help students deepen their understanding of the disciplinary core ideas . . . and develop a coherent and scientifically based view of the world" (p. 1).

These systems concepts work well to bridge scientific disciplines, but they can bridge wider divides as well. Similar ideas surface in the literature around 21st century skills (Jacobs, 2010), transferable skills (Vermont Agency of Education, 2014), and educating for sustainability (Cloud, 2010; Rogers, Pfaff, Hamilton, & Erkan, 2013; Shelburne Farms' Sustainable Schools Project, 2011). While there can be tension between these various branches of curriculum reform, it is useful to illuminate connections between them and the more targeted systems education ideas discussed above. Such connections could be central to effecting large-scale change (Plate & Monroe, 2014). The concept of systems literacy is intentionally defined through this study to be relevant across contexts.

2.3. Conceptualizing Systems Literacy

2.3.1. Overview. It has been valuable to consider several branches of complexity studies in working toward a rich and nuanced concept of systems literacy. Systems thinking—the most readily accessible of these branches, has been applied in K-12 education, where it is often but not always paired with system dynamics modeling (see, e.g., Fisher, 2011; Forrester, 2009; Plate & Monroe, 2014; Sweeney & Sterman, 2007). If all schools were to teach that much about complex systems (a solid grounding in interdisciplinary systems thinking with some experience pictorially and/or computationally building and exploring system dynamics models), this would represent a major step toward educating a systems literate society. However, systems thinking and system dynamics represent two among many approaches to studying complexity.

To conceptualize a fully developed definition of systems literacy, I have also looked to the less accessible, more esoteric branches of complex systems science and complexity theories. Imagining a society prepared to deal effectively with interconnected challenges across ecological, social, political, and economic systems, it has been useful to consider what it will take to educate effective scientists, professors, journalists, and politicians among others, to *lead* such a society. Arguably, such leaders must be *highly systems literate* (Plate & Monroe, 2014). Therefore this study has cast a wide net to consider what role the education system might play in scaffolding curricula to support students in developing the strongest possible foundation of systems knowledge and skills. It is the whole picture including the various overlapping branches of knowledge that defines this new way of thinking in the Age of Complexity.

2.3.2. Pieces of the literacy puzzle. A few authors have explicitly used the term *systems literacy* (see Bennett & Sweeney, n.d.; Dubberly, 2014; Plate & Monroe, 2014; Sweeney, 2014). Sweeney (2014), a leader in the field of systems thinking education, argued that children have an innate capacity to understand complex systems but that our traditional education system tends to dismantle this. She defined systems literacy briefly as "an applied understanding of living systems" (n.p.; see also Bennett & Sweeney, n.d.). "To be literate," she explained, "means to have a well-educated understanding of a particular subject, like a foreign language or mathematics." She went on to say,

> In many fields, the knowledge must be both comprehensive and abundant enough that you are capable of putting it to use. Systems literacy represents that level of knowledge about complex interrelationships. It combines *conceptual knowledge* (knowledge of system principles and behaviors) and *reasoning skills* (for example, the ability to see situations in wider contexts, see multiple levels of perspective within a system, trace complex interrelationships, look for endogenous or 'within system' influences, have awareness of changing behavior over time, and recognize recurring patterns that exist within a wide variety of systems). (p. 4)

Several authors and educators have outlined knowledge, skills, and dispositions central to systems thinking and system dynamics education. Sweeney (2014) outlined several concepts central to systems thinking including an awareness of the commons and general emphases on making connections, understanding change over time, seeing patterns, and changing perspective. Sterman (2002) identified additional concepts associated with system dynamics in particular, including "feedback, stocks and flows, time delays, and nonlinearity" (p. 501). In other branches of complexity, terms like *chaos theory*, *entropy*, *cybernetics*, *fuzzy boundaries*, and *fractals* enter the vocabulary.

Sterman (2002) argued that effective systems thinking requires not only an awareness of key terms but also the rigorous and disciplined use of scientific inquiry so that we can uncover our hidden assumptions and biases. It requires respect and empathy for others and their viewpoints. Most important, and most difficult to learn, systems thinking requires understanding that all models are wrong and humility about the limitations of our knowledge. (p. 501)

Sweeney (2009) argued that systems literate individuals recognize whole systems and their component parts and processes as decision-making contexts, understand the guiding principles of living systems, and develop habits of mind that serve them in approaching problems without immediately apparent resolutions. On her website, she outlined a series of twelve such habits of mind, which include seeing the whole, looking for connections, paying attention to boundaries, changing perspective, identifying stocks, challenging mental models, anticipating unintended consequences, tracking change over time, identifying oneself as "part of the system," embracing ambiguity, finding leverage, and being wary of win/lose attitudes (Sweeney, n.d.).

Table 2.1 below consolidates five distinct conceptions of systems skills. Sweeney's habits of mind, delineating the conceptual knowledge and reasoning skills discussed above, are listed in the far left column of that table. The Waters Foundation offered a very similar list in their Habits of a Systems Thinker card and poster sets. That list populates column two. Plate and Monroe (2014) articulated systems thinking skills somewhat differently. Their ideas are presented in column three.

In an essay titled "Systems Thinking: Critical Thinking Skills for the 1990s and Beyond," Richmond (1993) argued that three elements—educational process (specifically trends in education toward increasingly learner-directed learning), thinking paradigm (an evolution from linear, reductionist thinking to systems thinking), and the development of

Table 2.1

Systems Knowledge, Skills, and Dispositions

Habits of Mind	Habits of a Systems Thinker	Systems Thinking Skills	Critical Thinking Skills	Systems Literacy
Sweeney (n.d., n.p.)	*Waters Foundation (2014, n.p.)*	*Plate & Monroe (2014, p. 4-6)*	*Richmond (1993, p. 114-131)*	*Dubberly (2014, p. 3)*
"Sees the Whole"	"Seeks to understand the big picture"			
"Looks for Connections"	"Makes meaningful connections within and between systems"	"Recognizing Interconnections"	"Generic thinking"	
"Watches for Win/Lose Attitudes"			"Continuum thinking"	
"Embraces Ambiguity"	"Considers an issue fully and resists the urge to come to a quick conclusion"			
"Changes Perspective"	"Changes perspectives to increase understanding"	"Understanding Systems at Different Scales"		
"Looks for Stocks"	"Pays attention to accumulations and their rates of change"	"Differentiating Types of Stocks and Flows"		
"Anticipates Unintended Consequences"	"Identifies the circular nature of complex cause and effect relationships" "Considers short-term, long-term and unintended consequences of actions" "Recognizes that a system's structure generates its behavior"	"Identifying Feedback"	"Structural thinking"	"Systems *reading* skills (skills of analysis, for recognizing common patterns in specific situations, e.g., identifying—finding and naming—a feedback loop)"
"Challenges Mental Models"	"Surfaces and tests assumptions" "Considers how mental models affect current reality and the future"		"Thinking paradigm"	
"Looks for Change over Time"	"Observes how elements within systems change over time" "Recognizes the impact of time delays when exploring cause and effect relationships"	"Understanding Dynamic Behavior"	"Dynamic thinking"	
"Finds Leverage"	"Uses understanding of system structure to identify possible leverage actions"			
"Pays Attention to Boundaries"				
"Sees Self as Part of the System"			"Closed-loop thinking"	
			"Operational thinking"	
	"Checks results and changes actions if needed: 'successive approximation'"		"Scientific thinking"	
		"Incorporating Systems Thinking into Policies"		"Systems *writing* skills (skills of synthesis, for understanding and describing existing systems and for imagining and describing new systems)"
		"Creating Simulation Models"	"Learning tools"	
			"Learner-directed learning"	

new learning tools (computers and modeling software, in particular)—were “ripe for fusion” (p. 120). But, he argued, the problem remained of “how to equip teachers with an understanding of the framework, processes, and technologies of systems thinking” (p. 120). He delineated systems thinking as a series of seven specific critical thinking skills ranging from dynamic thinking (recognizing patterns of behavior and studying change over time) to scientific thinking (quantifying values and testing hypotheses), each of which he described in detail. (See Table 2.1, fourth column).

Another voice on systems literacy came from beyond the sphere of K-12 education. A design planner, teacher, and former creative services manager for Apple, Dubberly presented a keynote address at the Relating Systems Thinking and Design Symposium in Oslo, Norway in 2014. His talk, titled “A Systems Literacy Manifesto,” opened with the observation that in an age of political, economic, and environmental challenges, people have lost faith in the decision-making capacity of those in charge. He argued, “We need systems literacy—in decision makers and in the general public,” because the decisions that we face as leaders and as a society, almost always involve complexity (p. 2). Though Dubberly spoke about the need to teach systems concepts in design and management schools in particular, he also made the case that systems literacy should be a part of the curriculum in the general college setting and in K-12 education, “just as we teach language and math at all levels” (p. 2)

According to Dubberly, literacy in this context requires people to understand that “systems are complex (made of many parts, richly connected), dynamic (growing and interacting with the world), and probabilistic (easily disturbed and partly self-regulating—not chaotic, but not entirely predictable)" (p. 2). These attributes echo several of the concepts outlined in Sweeney's habits (Table 2.1, first column). Dubberly's description of systems literacy involved a particular vocabulary (including many of the same terms discussed by Sweeney, the Waters Foundation, Plate and Monroe, and Richmond) that when codified could facilitate interdisciplinary communication and collaboration. It also involved the dual processes of *reading systems* (recognizing common patterns in diverse contexts) and *writing systems* (communicating system structures and processes to others). These two concepts make up the final column of Table 2.1 and serve an important unifying role on that graphic.

With Dubberly's approach to literacy in mind, the vast majority of habits and skills outlined in the first four columns of that table fall most logically under the category of *reading.* Only a handful of concepts in the third and fourth columns align closely with the more active category of *writing.* Importantly, the habits, skills, and dispositions presented in the literature on systems education described in detail how systems literate individuals see the world and thus delineated key components of the content and context of systems literacy. However, they left room to develop a richer description of what one *does* with a systems worldview and how one might *contribute to* an emerging and evolving body of knowledge about complexity.

2.3.3. The history and canon of complexity. According to Dubberly, beyond vocabulary, reading, and writing, systems literacy should be rooted in a literary canon, a series of "key works of theory and criticism"; an historical context, a timeline of key players and the ideas that have moved the field forward; and a rich series of connections, "influences of systems thinking on other disciplines and *vice versa*" (p. 3-4). Grauwin et al. (2012) made the case that there is not a single systems theory, nor "a collection of theoretical books or articles revealing the 'universal' explanation." Instead, through their quantitative analysis of journal articles published on the theme of complexity in STEM fields, they uncovered "a variety of modeling disciplines" and a few common concepts including the defining characteristic of self-organization in complex systems and the central role of computers in studying them (p. 1,336). However, several texts have traced a basic history of complexity, and many identify works that have played key roles in the evolution of the field (see, e.g. Byrne & Callaghan, 2014; Capra & Luisi, 2014; Mitchell, 2009). Though there is not (and probably should not be) one canon or linear history of complexity, texts like these could serve as useful starting points for educators interested in developing a sense of context for their own systems literacy. With a better sense of context themselves, educators could identify the texts that might best introduce their students to the history and literature of complexity as appropriate to various content areas and developmental levels.

2.4. Becoming Systems Literate

Though none of them used the term *systems literacy*, several authors have described their own paths to complexity in the context of sharing key attributes of their respective fields. Wessels (2006), a field naturalist by training, articulated the importance of his childhood experiences in the woods, a theme that resonates with the literature on eco-literacy and educating for sustainability. Forrester (2007), the founder of system dynamics, presented a personal history to illustrate key aspects of that field. He opened that historical account by explaining that he grew up on a cattle ranch in Nebraska:

> A ranch is a crossroads of economic forces. Supply and demand, changing prices and costs, and economic pressures of agriculture become a very personal, powerful, and dominating part of life. Furthermore, in an agricultural setting, life must be very practical. It is not theoretical; nor is it conceptual without purpose. It is full-time immersion in the real world. (p. 345)

Connections to biological, ecological, and agricultural systems arose in multiple sources describing paths to complexity.

Forrester framed his personal history as a series of turning points. Accepted into an agricultural college, he decided instead to study electrical engineering. It was through electrical engineering that he was first introduced to theoretical dynamics. As a graduate student at MIT during the Second World War, he worked with a professor developing military technology. Throughout his narrative, he emphasized his experiences with practical applications for research, theory, and math. After the war, he was recruited to design an aircraft flight simulator.

> It was to be rather like an aircraft pilot trainer, except that it was to be so precise that instead of acting like a known airplane, it could take wind tunnel data of a model of a proposed plane and predict the behavior of the airplane before it was built. (p. 346)

These practical, cutting edge engineering experiences were the background he carried with him when he accepted a position leading MIT's new Sloan School of Management. It was in this position that he developed system dynamics, and it was at MIT that he started the work of applying system dynamics methods to complex problems in city planning and global development. He book *Urban Dynamics* (1969) led to his next book *World Dynamics* (1971) and to Donella Meadows' famous *Limits to Growth* (1972).

The eclectic background that Forrester described (from agriculture to engineering to business management to environmentalism) is one example of a common pattern among systems scholars. Byrne (2014), an expert on complexity theory in the social sciences, published an article titled "Thoughts on a Pedagogy OF Complexity," in which he not only pointed toward how he thought complexity might be taught (in particular at the upper-secondary and undergraduate levels) but also mapped his own path into and through the field. Like Forrester, he had a diverse educational background.

> The point is that accidentally I somehow got a very broad education including elements in Physiology, Biology and Physical Chemistry which paid serious attention to systems and I was at least competent in Calculus and rather more than competent in basic Statistics. . . . When I encountered complexity thirty years on in the 1990s, elements of all of this helped me to engage with it because I had a good deal of the vocabulary from the 'hard sciences' and mathematics already to hand. I had avoided the over specialization which is the bane of particularly English secondary education . . . I had been 'broadened'. (p. 44)

He argued that such broadening is an essential element of developing a complexity frame of reference and advocated for specifying "the pre-requisites for the sensible study of complexity in a way which facilitates this kind of broadening" (p. 44).

Byrne (2014) and Sterman (2002) both articulated the importance of a critical approach to developing systems dispositions. Byrne wrote about "reconstructing patterns of belief" through "the notion of 'the scientific method" (p. 46). He connected his thoughts on pedagogy to Freire's (2000) ideas about banking education, power relationships, and the formalization of official knowledge. Along these lines, Sterman (2002) emphasized the power of mental models. "One of the goals of system dynamics," he explained, "is to expand the boundaries of our mental models, to lengthen the time horizon we consider so we can see the patterns of behavior created by the underlying feedback structure, not only the most recent events" (p. 511). Doing this, he said, requires crossing boundaries between disciplines, departments, and areas of specialization. "It requires breaching barriers erected by culture and class, by race and religion" (p. 511). Continually challenging our own mental models, he explained, can help us to uncover our own biases and work toward authentic solutions and progress. We do this, he said, by asking "why" questions, and in this way, "we gain insight into how we are both shaped by and shape the world, where we can act most effectively, where we can make a difference—and what we are striving for" (p. 527).

2.5. The Purpose of Systems Literacy

Systems scholars often ground their writing about systems education in a deep sense of purpose. For example, Forrester (2009) argued that a systems dynamics education should

> (1) Sharpen clarity of thought and provide a basis for improved communication, (2) Build courage for holding unconventional opinions, (3) Instill a personal philosophy that is consistent with the complex world in which we live, (4) Reveal the interrelatedness of physical and social systems, and (5) Unify knowledge and allow mobility among human activities. (p. 5)

Sweeney (2014) argued that increasing systems literacy would increase students' compassion for others and help children "to see themselves as part of, rather than outside of, nature" (p. 4). "As they grow up and learn about the economy, climate, education, energy, poverty, waste, disease, war, peace, demographics, and sustainability," she wrote, "children who are systems literate will tend to look at all these issues as interrelated" (p. 4). Kagan (2010) connected systems thinking to "cultures of sustainability." He identified it as "a specific language that allows transdisciplinary work and could serve as one of the bases for cultures of sustainability" (p. 1096). Dias (2015) argued that systems understandings of creativity and imagination could support students in developing skills for thriving in changing times. "The imperative to prepare children with capacities to flourish in their futures," she argued, "is never more urgent than now, when change and unpredictability are fast becoming our most reliable constants" (n.p.).

Dubberly (2014) also emphasized the importance of supporting students in developing systems knowledge, skills, and dispositions. He argued,

> We have a responsibility to try to make things better. If we want decision makers to have a basis to judge the effects of their decisions, or if we acknowledge that almost all the challenges that matter—and most social and economic innovation—involve systems, and if we know that tools exist to help us think about systems, then we must put those tools into circulation. We must build systems literacy. To not do so would be irresponsible. (Dubberly, 2014)

Our education system has a central role to play in supporting all students in developing basic levels of systems literacy and supporting many students in reaching higher. As Sweeney (2009) wrote, "Without these skills, we continue to operate from crisis to crisis, stuck on the problem solving treadmill, where our ‘solutions’ often only create more problems or make the original problem worse" (n.p.). But if we can successfully develop such skills across the education system, “we will have a generation of people who will actually think differently" (Fisher, 2011, p. 406).

Before that work can happen in a cohesive way, educators need a more fully developed definition of systems literacy and its various properties, dimensions, and contexts as well as a working understanding of how one becomes systems literate. This study has advanced that work.

Chapter 3: Research Methods

3.1. Overview

This chapter details the frameworks and methods employed throughout this study on systems literacy. Section 3.2 introduces the *Literacy in 3D* model I used to frame a definition of systems literacy. Second 3.3 describes the complexity frame of reference that informed my research process. Section 3.4 offers an overview of some defining features of grounded theory, and definitions of key terms; 3.5 explains why this methodology was well suited to complexity-informed research on systems literacy. Sections 3.6 through 3.10 describe how I employed these methods throughout the iterative study of which this dissertation is a part.

3.2. Conceptual Framework: *Literacy in 3D*

To expand upon the working definitions of systems literacy in the literature, it was helpful to have a concrete conceptual framework. The *Literacy in 3D* model was first developed by Green in 1988 (Green & Beavis, 2012). In this model, Green identified subject-specific literacy as "the particular literacy, or set of literacy competencies, that is inextricably part of the operation of specific subject areas as contexts for learning and meaning" (Green & Beavis, 2012, p. 3). The model emphasizes writing (a particularly active form of learning) over reading alone, posits that *thinking* and *meaning* (both verbs) can be seen as "the real 'basics'" of literacy (p. 4), and defines literacy across three overlapping dimensions: the cultural, operational, and critical.

The cultural dimension is closely linked with content and context. Green argued, "to learn culture and to become an effective, functioning participant in culture, involves learning the language and becoming competent with regard to using it as a resource for meaning" (p. 5). This dimension involves the conventions of subject-specific communication and connects with questions of the purpose of and audience for the work at hand (p. 122). The operational dimension, on the other hand, is closely linked with the ways people use language to operate and communicate effectively within particular contexts. It involves the skills and knowledge required to undertake tasks or engage in activities to develop and convey meaning (p. 122).

While being operationally and culturally literate offers one "access to the meaning system of the culture" and the potential to "function in it effectively and productively" (p. 7), the critical dimension emphasizes the fact that such meaning systems, representing selected knowledge, are not neutral. Therefore, Green argued, we must be explicit in teaching students "the grounds for selection and the principles of interpretation" of knowledge, giving them "more critical insight into the processes and possibilities of knowledge production, their own and that of the culture" (p. 7). The critical dimension challenges educators to consider their choices in terms of content and pedagogy to empower learners "not simply to participate in culture but also, in various ways, to transform and actively produce it" (p. 7).

Over the past few decades, Green's model has been applied to evolving forms of literacy in information technology, media literacy, and numeracy and has been employed in the contexts of pedagogy, teacher training, and research. The model's three interdependent dimensions provide a concrete framework for conceptualizing subject-specific literacies. Taken together, the cultural emphasis on content, the operational emphasis on skills, and the critical emphasis on the creative, transformative potential of active learning helped to inform a robust definition of systems literacy.

3.3. Theoretical Framework: The Complexity Frame of Reference

This study is not only *about* complexity (and its implications for education); it is also informed *by* complexity. As discussed above, there is no one accepted version of complexity theory (Byrne & Callaghan, 2014; Geert & Steenbeek, 2014; Mitchell, 2009; Umphrey, 2002). Because it has arisen concurrently across a range of traditions, it has taken on different forms in different contexts. However, in a recent book *Complexity Theory and the Social Sciences: The State of the Art*, Byrne and Callaghan (2014) compiled much of the emergent canon and history of complexity to synthesize what they identified as the *complexity frame of reference.* They described the complexity frame of reference as a particular ontological approach to the world rooted in complex realism, existing at the intersection of complexity theory and critical realism (p. 9).

Byrne and Callaghan's approach to the world through the complexity frame of reference aligns well with Green's three dimensions of literacy. Emphasizing the role of narrative in meaning making, their own story of complexity offered insights into cultural aspects of systems literacy. They reflected extensively on methodological approaches to complexity, problems and possibilities connected with operational literacy. Finally, they were critical in their approach, describing clear differences between restrictive and general models of complexity and articulating criteria for including and rejecting particular aspects of various traditions. Their thorough but pragmatic approach to complexity drew from a wide range of disciplines in describing "the state of the art" and pointing toward the future of post-disciplinary complexity studies in the social sciences. This study was informed by complexity and systems theories in general, but by Byrne and Callaghan's complexity frame of reference in particular.

3.4. Grounded Theory

This study has employed grounded theory methods informed by a complexity frame of reference. A qualitative approach to inquiry, grounded theory is designed for open-ended exploration and discovery (Patton, 2002). Because associated methods result in rich descriptions of concepts and theories of process (Corbin & Strauss, 2008), they were a good fit for my core research questions: *What is systems literacy?* and *How does one become systems literate?* With disciplinary roots in the social sciences, grounded theory is implemented across a wide range of social science fields today (Creswell, 2013; Patton, 2002). The methods consist of systematic guidelines for drawing patterns out of raw data (Denzin & Lincoln, 2000). Adhering to prescribed strategies is thought to increase standardization and rigor of qualitative research methods (Patton, 2002). A grounded theory study can conclude with rich descriptions of the phenomenon of interest, but the methods were originally designed to carry the process of description further into the generation of theory (Corbin & Strauss, 2008; Denzin & Lincoln, 2000; Patton, 2002). In this context, theory is not produced through logical deduction based on "a priori assumptions" (Patton, 2002, p. 125). Instead, it is built out of the observations of a researcher interacting with participants in the real world (Creswell, 2013; Denzin & Lincoln, 2000; Patton, 2002). Thus the theory emerges from analysis of data and is empirically grounded (Byrne & Callaghan, 2014; Patton, 2002).

Data collection methods are relatively open-ended (Charmaz, 2000). They typically involve semi-structured interviews, though other strategies (e.g. surveys, document analysis, etc.) are acceptable (Patton, 2002). Raw data is gathered based on conceptual leads (a method known as *theoretical sampling*); unpacked in terms of categories, properties, and dimensions (referred to in this document as "variations" to avoid confusing grounded theory "dimensions" with the "dimensions" of the *Literacy in 3D* model); and reconstructed in terms of patterns, processes, and narrative explanations with attention not only to common attributes of participants' ideas and experiences, but also to differences and exceptions to emerging theoretical constructs.

Though approaches to grounded theory vary in detail and philosophical orientation, ranging from highly objectivist (as in Glaser's approach) to highly constructivist (as in Charmaz's), the defining features are fairly consistent (Charmaz, 2000). Several of these are defined and described in sections 3.4.1 through 3.4.5 below. Importantly, the purpose of grounded theory is to build theory rather than to test it (Patton, 2002; Strauss & Corbin, 1998). As such, the methods are excellent for generating ideas, grounding knowledge in context and experience, and opening conversations rather than closing them.

3.4.1. Theory. Several terms are central to grounded theory methods, and their definitions guide and structure the work of the researcher. The most important is a particular understanding of the word *theory.* Strauss and Corbin (1998) defined a theory as "a set of well-developed concepts related through statements of relationship, which together constitute an integrated framework that can be used to explain or predict phenomena" (p. 15). Unlike traditional a priori theoretical constructions, a grounded theory is an emergent phenomenon, generated inductively through fieldwork (Byrne & Callaghan, 2014; Creswell, 2013; Linden, 2006; Patton, 2002). Grounded theorists focus on theories of process or action (Charmaz, 2000; Corbin & Strauss, 2008; Creswell, 2013), developed in terms of five key components: "a central phenomenon, causal conditions, strategies, conditions and context, and consequences" (Creswell, 2013, p. 90).

3.4.2. Concepts, categories, properties, and dimensions. Rather than aiming for findings representative of populations, grounded theorists are concerned with *concepts*—ideas contained in data—and studying individuals and incidents that might illuminate patterns and variations within concepts (Corbin & Strauss, 2008). Through analysis, some concepts are raised to the level of *categories* representing the ideas and experiences of multiple people or groups. Categories represent individuals' stories "reduced into and depicted by several highly conceptual terms" (p. 103). Often several codes are subsumed into a single category representing major ideas or happenings to which lower level concepts point (Charmaz, 2000; Corbin & Strauss, 2008). Categories are divided into *properties*, which Corbin and Strauss (2008) defined as "characteristics that define and describe concepts" and dimensions, "variations within properties that give specificity and range to concepts" (p. 159).

3.4.3. Theoretical sampling for comparative analysis. Concepts not only emerge out of the data; they also drive further collection through *theoretical sampling* (Charmaz, 2000; Corbin & Strauss, 2008). Theoretical sampling is designed for exploring relatively uncharted areas of study and uncovering variation between cases. Its purpose is to develop and refine emerging ideas; because sampling is responsive to data, it cannot be fully planned in advance (Corbin & Strauss, 2008). As a dynamic process, it "permits elucidation and refinement of the variations in, manifestations of, and meanings of a concept as it is found in the data," and it "supports the constant comparative method of analysis" (Patton, 2002, p. 239).

Comparative analysis involves comparing and contrasting incidents in search not only of patterns and common characteristics but also of variation and negative cases (Corbin & Strauss, 2008; Linden, 2006). Such analysis can involve comparing different people in terms of their views, experiences, etc., comparing the views of a single person as expressed at one point in time versus another, comparing incident to incident, category to category, and/or data with corresponding categories (Charmaz, 2000). Comparative analysis informs sampling in a cyclical fashion as new data points toward either saturation or conceptual gaps (Creswell, 2013).

3.4.4. Coding. *Coding* is the process of "taking raw data and raising it to a conceptual level" (Corbin & Strauss, 2008, p. 66). The process is not linear, but different types of coding serve particular purposes at different stages in a study. *Open coding* is used first to break data apart, to identify categories, properties, and dimensions (Corbin & Strauss, 2008; Creswell, 2013; Patton, 2002; Strauss & Corbin, 1998). *Microanalysis*, a specific form of open coding, involves close reading to get the researcher deep into raw data to generate ideas; these emerging ideas are checked against data, and interpretations are reinforced, revised, or discarded (Corbin & Strauss, 2008). Microanalysis and open coding require an open-minded approach to avoid what Miles and Huberman (1994) refered to as "premature analytic closure" (p. 69-70).

Axial coding is the process of making connections between categories and subcategories (Charmaz, 2000; Corbin & Strauss, 2008; Patton, 2002; Strauss & Corbin, 1998). Having broken data into manageable pieces through open coding, the purpose of axial coding is to reassemble those pieces and illuminate relationships between ideas. At this stage, a core phenomenon serves as the axis of analysis, and categories are linked through their properties and dimensions (Strauss & Corbin, 1998). The task is to identify "*causal conditions* (what factors caused the core phenomenon), *strategies* (actions taken in response to the core phenomenon), *contextual* and *intervening conditions* (broad and specific situational factors that influence the strategies), and *consequences* (outcomes from using the strategies)" (Creswell, 2013, p. 86).

A final form of coding is *selective coding* (Charmaz, 2000; Corbin & Strauss, 2008). As opposed to microanalysis, which can be used to study data line-by-line to uncover new concepts, selective coding uses codes that have occurred frequently through analysis to process data in bulk (Charmaz, 2000). It serves the purpose of refining categories and integrating them into a story or model—a theory—that describes the phenomenon under study (Creswell, 2013; Strauss & Corbin, 1998). Data collection and analysis (coding and memoing) occur not as distinct stages but rather cyclically through a grounded theory study. "Through the process of constant comparative analysis, the analyst collects, examines, compares, and re-collects (dependent on the data) to discover a 'core variable' that indicates the root or essence of what is going on within the system studied" (Toscano, 2006, p. 509).

3.4.5. Memoing toward saturation. The cyclical process of data collection and analysis is complete when the categories reach *saturation*. At this point categories are richly developed, variation is accounted for, relationships between concepts are clear, and new data fits existing codes and categories (Charmaz, 2000; Corbin & Strauss, 2008; Patton, 2002). *Memoing* is a key strategy in reaching saturation (Corbin & Strauss, 2008; Creswell, 2013). Memoing helps to spark creative and critical thinking about data by pointing the researcher toward new ideas and new ways of seeing and illuminating gaps to sample forward (Charmaz, 2000). Corbin and Strauss (2008) described memos as "running logs of analytic thinking" and encouraged the researcher to write these after every session of analysis (p. 108, 120).

Grounded theory strategies "ground" the researcher in the data. This form of qualitative inquiry is inductive in its early stages, allowing for "embedded meanings and relationships" to emerge from the data (Patton, 2002, p. 453-54). Through cycles of data collection, coding, memoing, and sampling forward, analysis becomes increasingly focused as it builds theory out of concepts emerging from the field.

3.5. Grounded Theory and Systems Literacy

3.5.1. Topical fit. Grounded theory offers structured methods for filling the gap when a process exists without a corresponding theory to explain it or when existing models and theories are somehow limited (Creswell, 2013). For this reason, grounded theory's exploratory approach was well suited to this study. Though explanatory frameworks related to systems literacy did exist, as described in chapter 2, each was limited in some way. Applying Green's Literacy in 3D model (focusing on the cultural, operational, and critical dimensions of literacy) as a conceptual framework for analysis allowed me to build on the work of Sweeney (2014), Dubberly (2014), and others to create a more robust definition of systems literacy. And though authors have offered compelling reasons for *why* we should be developing students' systems literacies (e.g., Dubberly, 2014; Sweeney, 2009, 2014) or described their own paths to complexity (e.g., Byrne, 2014; Forrester, 2007), none have provided a formal theory of *how one becomes* systems literate.

3.5.2. Theoretical fit. Grounded theory was fitting not only to the topic and goals of this study but also to its theoretical underpinnings. Research informed by a complexity frame of reference must address a series of challenges: (1) the challenge of balancing analytic reductionism with more holistic approaches to knowledge; (2) the challenge of developing new knowledge in the context of continuous change; (3) the challenge of accommodating conflicting ontologies, different ways of knowing and communicating about the world rooted in diverse disciplinary traditions; and (4) the challenge of locating knowledge within the contexts of time, place, and experience (see Cundill, Fabricius, and Marti, 2005; Patton, 2002; Umphrey, 2002).

Grounded theory is well equipped to address these challenges (Byrne & Callaghan, 2014; Corbin & Strauss, 2008; Linden, 2006; Patton, 2002; Stillman, 2006; Toscano; 2006). First, grounded theory analysis involves a breaking apart of data, a process of relating codes to one another to form categories and concepts, and a synthesis of concepts to identify patterns and processes (Creswell, 2013). It is both reductive/analytic and synthetic/constructive by design. Second, it is up to the challenge of generating practical knowledge in a changing world (Byrne & Callaghan, 2014). Grounded theories, emerging through observation of and interaction with participants and their worlds, are not fixed artifacts. Rather, they are explanations of data open to testing, refinement, and revision through further research (Linden, 2006; Stillman, 2006). Corbin and Strauss (2008) aligned this understanding of theory with two key assumptions from the Pragmatic tradition: “One is that truth is equivalent to ‘for the time being this is what we know—but eventually it may be judged partly or even wholly wrong.’ Another assumption is that despite that qualification, the accumulation of knowledge is no mirage" (p. 4).

Third, a complexity-informed approach to grounded theory takes into account multiple, even conflicting traditions. In her updated edition of the co-authored text *Basics of Qualitative Research*, Corbin discussed how the postmodernist, deconstructionist, and constructivist schools of thought had influenced her evolving ideas about qualitative research (Corbin & Strauss, 2008). Because systems literacy is such a deeply interdisciplinary concept, each of these traditions is relevant. For this reason, Corbin and Strauss's modern form of grounded theory is particularly well suited to developing nuanced theories informed but not constrained by conflicting traditions. Finally, Corbin and Strauss (2008) argued that understanding experience requires that experience to be located within, not divorced from "the larger events in a social, political, cultural, racial, gender-related, informational, and technological framework." These elements, the authors explained, "are essential aspects of our analyses" (p. 8).

Studying complexity is about understanding the dynamic, interdependent systems that constitute the world around us. History and context are deeply relevant, as is the real-world applicability of findings. This study is a product of its time and place, the context established in previous chapters. Through this study, I have consolidated current knowledge around complexity studies and, through action and interaction with study participants, created something new, a rich description of systems literacy and a theory of how one becomes systems literate.

3.6. Research Design

A Study in Three Phases

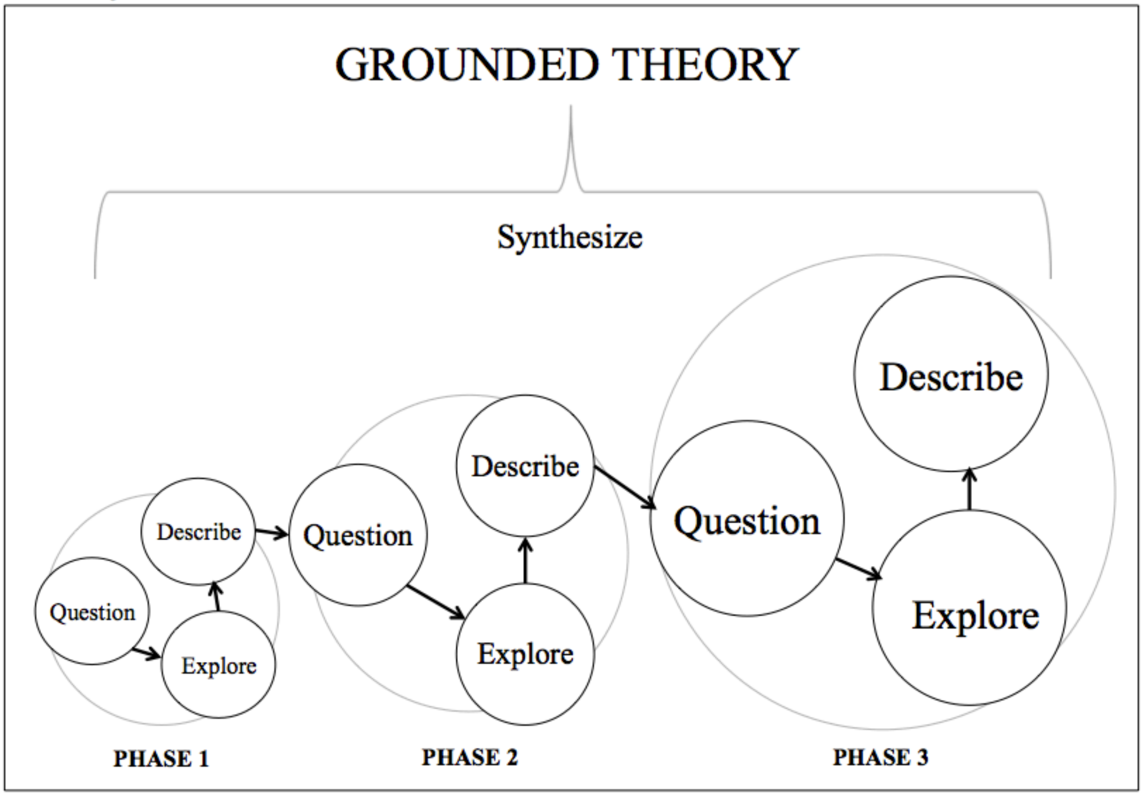

Figure 3.1. Research as an iterative process

I began this study as a pilot project in the fall of 2013, scaled it up in the spring of 2014, and expanded it once again as a dissertation. I describe each of these three phases in detail below. Though the entire study may be represented as a first round of exploratory research, a second of descriptive, and a third of theory building, in fact, each phase incorporated all three modes of inquiry. (See Figure 3.1. Research as an iterative process above.) The following sections specify how I applied grounded theory methods throughout the extended study. The first three sections delineate sampling procedures; participant selection; and setting, access, and ethical considerations. Data collection and analysis procedures (iterative and overlapping by design) are described as they occurred in each of the study's three phases. The final three sections of this chapter explore the background and role of the researcher, point toward study limitations, and discuss steps taken to insure validity of findings.

3.6.1. Sampling. The first phase of this study employed what Patton (2002) described as theory-based sampling, a method in which "the researcher samples incidents, slices of life, time periods, or people on the basis of their potential manifestation or representation of important theoretical constructs" (p. 238). In phase two, selection of participants was informed by both theory-based sampling and theoretical sampling as I followed not only hunches but also data into new interviews. In phase three, theoretical sampling, informed by the concepts emerging from the data, was the dominant method for driving further collection. It informed not only my recruitment of participants (described in the next section) but also my selection of texts to analyze as data sources (described in the section titled "Phase Three, the Dissertation" below).

3.6.2. Participants. Through each phase of this study, I engaged a diverse set of participants to explore common patterns and variations within concepts (Corbin & Strauss, 2008). My target population was professionals who study, conduct research in, and/or teach complex systems concepts. The three participants in my pilot study included a professor of computer science, a professor of public administration, and a 7th-12th grade science teacher. As I expanded that group in phase two, I added professors teaching at the undergraduate and graduate levels across a wider range of disciplines and two more teachers, one teaching high school science and food systems, the other, high school social studies. In phase three, I added one more professor (specifically looking to capture another voice from the humanities) and three women (an underrepresented group in my existing sample) all of whom worked in professional development teaching systems-related concepts to educators. The full sample is presented in Table 3.1 below.

Table 3.1

Participants

Pseudonym	Profession	Department/Domain
Alex	Professor	Mathematics and Statistics
Ben	Middle/high school teacher	Science
Beth	Professional developer	K-12 Education
Bob	Professor	Classics
Charlotte	Professor	Computer Science
Daniel	Professor	Public Administration and Policy
Dawn	Professor	School of Engineering
Elizabeth	Educator	K-12 and Teacher Education
Emmett	Professor	Communication Management and Design
Ethan	Professor	Anthropology and Archaeology
Gavin	High school teacher	Social Studies
Genevieve	Professional developer	K-12 Education
Henry	Professor	Public Administration and Policy
Jake	Professor	Environmental Studies and Sciences
Madeline	Professor	Biochemical Engineering
Matt	Professor	Electrical Engineering
Max	High school teacher	Science and Food Systems
Nick	Professor	Comm. Development and Applied Economics
Noah	Professor	Political Science
Oliver	Professor	Information Technology
Simon	Professor and dean	Environmental Humanities
William	Professor	Mathematics and Statistics

The final sample of 22 participants was drawn from twelve institutions including seven colleges and universities, three middle and/or high schools, and two professional development organizations. They included six women and sixteen men ranging in age from their early thirties to early seventies. While I actively sought diversity on a range of variables (from gender and age to geographical location), I focused in particular on recruiting participants from a wide range of disciplines and domains. Through theory-based sampling, I worked on the assumption that the theme of complexity would illuminate commonalities among these disparate fields. Through theoretical sampling, I sought not only those commonalities, but also the variations between them.

According to Corbin and Strauss, "Researchers are the go-betweens for the participants and the audiences that they want to reach" (p. 49). This study provided opportunities for me to converse with educators and scholars, many of whom shared excellent ideas about the intersections between systems thinking, complexity, and education. My goal was to synthesize some of those ideas into a form that is meaningful to K-12 educators.

3.6.3. Setting, access, and ethical considerations. All participants were invited personally to participate in this study. Some I met through my university work, others I knew from my work in schools. Still others I met in professional settings, was referred to by other participants, or found online by searching for programs that teach curricula rooted in systems concepts. Most participants were recruited via email. Some were invited in person. As much as possible, interviews were conducted in participants' offices or classrooms. Because of the nature of my questions, the academic setting was appropriate. When geographic distance would have been a barrier, I conducted interviews via Skype™ or Google Hangouts. The technology facilitated audio recording on my computer (which I could not do over the phone) and helped to make interviews friendly and engaging, as body language and facial expressions contribute much in video calls. I audio-recorded all interviews and stripped names and other identifying details from transcriptions. Participants are identified by pseudonym throughout the study. This research was deemed exempt by the University of Vermont's Internal Review Board (IRB). (See Appendix 7.1. IRB Forms.)

3.7. Three Phases of Research

3.7.1. Phase one. In the fall of 2013, with a general interest in complex systems as an interdisciplinary theme in education, I interviewed and surveyed three participants including two college professors and one middle/high school teacher, all of whom worked with systems concepts and methods across diverse fields. My goal with this project was to uncover common themes in participants' interests, experiences, skills, and dispositions. To that end, I developed a series of questions:

1. How do academics and professionals from a range of traditional disciplines come to the study of complex systems?
    a. What educational and life experiences, understandings, and big questions led them to that work?
    b. What skills did they need to develop to pursue complex systems research?
2. How might we inspire and prepare the next generation of academics to study complexity?
    a. What foundational knowledge and skills do they need to develop?
    b. What will today's high school students need to know and be able to do in order to contribute to that conversation, no matter what particular field inspires them most?
    c. What roles do, could, or should high schools play in that trajectory?

Ideas from interviews and surveys with my first few participants uncovered these six preliminary findings describing skills and dispositions required for grappling with complex systems:

1. A love of science in general, but a fascination with the natural sciences of biology and ecology in particular, is a common precursor to working with complex systems.
2. Computational capacity is important, but understanding math conceptually is at least as important as being able to crunch the numbers.
3. Computers are essential tools in complex systems studies.
4. Complex systems scientists see connections between diverse ideas and contexts.
5. Advancing knowledge in complex systems requires a collaborative approach.
6. Complex systems scientists are adept at independent learning. They seek out new information and synthesize new knowledge.

These concepts informed development of a survey and interview protocol for the second phase of this study. (See Appendix 7.2. Systems Skills Inventory and Appendix 7.3. Phase Two—Interview Protocol.) The pilot project, though limited in scale, provided me with a great deal of data to explore, code, and consider as I refined my research questions going forward.

3.7.2. Phase two. The following spring I scaled the study up, interviewing thirteen more professors from several colleges and universities and two more high school teachers. All eighteen participants conducted research in and/or taught complex systems concepts at the middle school, high school, college, and/or graduate level. Phase two interview questions ranged across a series of topics, but they were all aimed at aspects of these two research questions:

1. What skills did complexity scholars across a range of fields need to develop in order to pursue these lines of inquiry?
2. What will today's students need to know and be able to do in order to contribute to that conversation?

With more participants, I was able to fine-tune and solidify the six concepts revealed in the pilot project, identify and substantiate three more, and develop a better sense of the properties and variations of each. In the resulting paper titled *The Complexity Paradigm in Education: Skills and Dispositions for Grappling with Complex Systems*, I presented nine preliminary findings, descriptive concepts outlining skills and dispositions that—though they varied in detail across participants' experiences—arose as distinct patterns in this group of complexity scholars as a whole. Briefly, these findings included (1) scientific knowledge and inquiry, (2) seeing connections, (3) perspective, (4) multi-modal communication skills, (5) collaboration, (6) math skills, (7) computing, (8) data analysis, and (9) active learning skills (Steele, 2015).

3.7.3. Phase three, the dissertation. Patton (2002) explained,

> As fieldwork begins, the inquirer is open to whatever emerges from the data, a discovery or inductive approach. Then, as the inquiry reveals patterns and major dimensions of interest, the investigator will begin to focus on verifying and elucidating what appears to be emerging—a more deductive approach to data collection and analysis. In essence, what is discovered may be verified by going back to the world under study and examining the extent to which the emergent analysis *fits* the phenomenon and *world to explain* what has been observed. (p. 67)

Phases one and two of this study were highly exploratory. They resulted in rich description but did not carry analysis forward to identify a unifying core category; nor did they explore process to build toward theory. Through phase three, my dissertation, I completed this work. With a series of interrelated categories in hand, I returned to the literature where I found what would become an overarching core category, the phenomenon of *systems literacy*. From there I developed research questions to define that core category and to explore a central process, *how one becomes systems literate.*

3.7.4. Defining systems literacy. Though relatively few authors and educators have used the term *systems literacy* in their writing, many systems thinking and system dynamics educators have developed tools and published texts outlining knowledge, skills, and dispositions relevant to this core concept. I selected five such resources to analyze as data sources in the third phase of this study. (See Table 3.2 below.)

Based on earlier analysis, I did already have ideas about what I might find in this new data, so digging in deeply through a combination of open and axial coding was central to uncovering new concepts, properties, and variations. Memos at this stage of analysis emphasized breaking data down to reflect on particular details and ideas (Corbin & Strauss, 2008). My core category served as a connective lens as I explored these new data sources to refine concepts developed in earlier phases while remaining open to new ideas. Twelve codes emerged through that process (active learning, communication, connections, content, critical realism, cross-discipline, dynamics, holistic, mental models, perspectives, reading systems, and scientific inquiry), and I used these twelve codes to reanalyze my first eighteen transcribed interviews.

Table 3.2

Text-Based Data Sources for Defining Systems Literacy

Author	Text	Year	Domain
Dubberly	"A Systems Literacy Manifesto"	2014	Software design
	Snapshot of concepts: "Systems vocabulary . . . systems reading skills . . . systems writing skills . . . the literature of systems . . . the history of systems . . . connections [between systems, disciplines, domains, and methods]" (n.p.)		
Plate & Monroe	"A Structure for Assessing Systems Thinking."	2014	Systems thinking and system dynamics education
	Snapshot of concepts: "Recognizing interconnections . . . identifying feedback . . . understanding systems at different scales . . . differentiating types of stocks and flows . . . understanding dynamic behavior . . . creating simulation models . . . incorporating systems thinking into policies" (p. 4-6)		
Richmond	"Systems Thinking: Critical Thinking Skills for the 1990s and Beyond"	1993	Systems thinking and system dynamics education
	Snapshot of concepts: "Dynamic thinking . . . closed-loop thinking . . . generic thinking . . . structural thinking . . . operational thinking . . . continuum thinking . . . scientific thinking . . . educational process . . . thinking paradigm . . . learning tools" (p. 114-131)		
Sweeney	"12 Habits of Mind"	(n.d.)	Systems thinking and system dynamics education
	Snapshot of concepts: "Sees the whole . . . looks for connections . . . pays attention to boundaries . . . changes perspective . . . looks for stocks . . . challenges mental models . . . anticipates unintended consequences . . . looks for change over time . . . sees self as part of the system . . . embraces ambiguity . . . finds leverage . . . watches for win/lose attitudes" (n.p.)		
Waters Foundation	"Habits of a Systems Thinker"	2014	Systems thinking education
	Snapshot of concepts: "Seeks to understand the big picture . . . observes how elements within systems change over time . . . recognizes that a system's structure generates its behavior . . . identifies the circular nature of complex cause and effect relationships . . . makes meaningful connections within and between systems . . . changes perspectives to increase understanding . . . surfaces and tests assumptions . . . considers an issue fully and resists the urge to come to a quick conclusion . . . considers how mental models affect current reality and the future . . . uses understanding of system structure to identify possible leverage actions . . . considers short-term, long-term and unintended consequences of actions . . . pays attention to accumulations and their rates of change . . . recognizes the impact of time delays when exploring cause and effect relationships . . . checks results and changes actions if needed: 'successive approximation'" (n.p.)		

The *Literacy in 3D* model informed my selective coding, and I used graphic organizers and tables extensively to synthesize coded data into categories describing the three dimensions (cultural, operational, and critical) of systems literacy. I kept a running log of adaptations to these visual tools in my memos where I also recorded narrative and descriptive representations of my thoughts and processes. Through that process, I developed a working definition of systems literacy.

Next, I recruited four new participants. Interviews in this phase, as in each phase before, were semi-structured. (See Appendix 7.4. Phase Three—Interview Protocol.) As such, I remained "free to follow up on questions without concern of whether or not the same question was asked of previous participants" (Corbin & Strauss, 2008, p. 148). I started each conversation by asking for feedback on my definition. Participants' feedback informed revisions (described in detail in the "Validity of Interpretation" section below). I then asked each participant if he or she considered him or herself systems literate (to which all replied with a qualified "yes") before asking a series of questions to get at how he or she became systems literate.

3.7.5. Becoming systems literate. While I was conducting this research, the book *Journeys in Complexity: Autobiographical Accounts by Leading Systems and Complexity Thinkers* was published. Edited by Montuori (2015), the book is a compilation of essays, in which authors identified and described key experiences in their lives leading to their current understandings of and work within the field of complexity studies. This text was highly relevant to my research. I read all eleven of the essays and included nine of them in my final analysis. (Of the two I did not include, one was the editor's introduction. Regarding the other, I wrote this note in my memos: "Doesn't contradict any of my findings, but probably won't use—too metaphysical.") Additionally, I decided to analyze three essays I had read for my literature review as data sources, because in each of these the authors also wrote at some length about the experiences that led them to their work with complexity. (See Table 3.3 below.)

Table 3.3

Texts Analyzed as Data Sources for Becoming Systems Literate

Author	Title	Published In	Year
Burneko, G.	"The Starry Night Sky"	*Journeys in Complexity*	2015
Byrne, D.	"Thoughts on a Pedagogy OF Complexity"	*Complicity: An International Journal of Complexity and Education*	2014
Combs, A.L.	"My Life in Chaos"	*Journeys in Complexity*	2015
Eisler, R.	"Human Possibilities: An Integrated Systems Approach"	*Journeys in Complexity*	2015
Forrester, J.W.	"System Dynamics—A Personal View of the First Fifty Years"	*System Dynamics Review*	2007
Goerner, S.J.	"Bringing Forth That Which Is Within: How an Invisible Hand Led Me to a Life . . ."	*Journeys in Complexity*	2015
Low, A.	"Introduction: The Complexity of Life and Lives of Complexity"	*Journeys in Complexity*	2015
Montuori, A.	"Complexity and Transdisciplinarity: Reflections on Theory and Practice"	*Journeys in Complexity*	2015
Ogilvy, J.	"Systems Theory, Arrogant and Humble"	*Journeys in Complexity*	2015
Olds, L.E.	"Systems Patterns and Possibilities"	*Journeys in Complexity*	2015
Sahtouris, E.	"A Passion for Pushing the Limits"	*Journeys in Complexity*	2015
Sterman, J. D.	"All Models Are Wrong: Reflections on Becoming a Systems Scientist"	*System Dynamics Review*	2002

For each text, I generated a document including relevant quotations to be coded. I also recoded all 22 transcribed interviews in a new round of analysis. Twelve texts and 22 interviews provided me with 34 cases to analyze in all. Comparative analysis of a wide range of diverse perspectives was central to this study (Corbin & Strauss, 2008). In developing a theory of process, examining difference holds great potential for uncovering patterns of *equifinality*, a term Byrne and Callaghan (2014) use to describe "multiple paths towards the same outcome" (p. 202)

In this third phase, while the first round of analysis, emphasizing open coding, served the primary purpose of pulling data apart to identify and catalog distinct concepts and details, the second round, emphasizing axial and selective coding, focused primarily on synthesizing information and generating theoretical ideas (Corbin & Strauss, 2008). The practice of zooming in to study details and zooming out to gain perspective and identify interconnectivity is important in complexity informed research (Richmond, 1993). Again, tables and graphic organizers were central to my analysis as I explored the process of becoming systems literate for patterns among and differences between participants' described experiences. Through open and axial coding and extensive memoing, I developed and refined five categories to describe the process of becoming systems literate. Those are described at length and in terms of their properties and variations in the second journal article in chapter four of this document. Briefly, they are *grounding*, *questioning*, *broadening*, *integrating*, and *developing a systems lens.* My cyclical process of data analysis and collection was complete when I had enough and understood enough to tell "a coherent overarching story" about the process of becoming systems literate (Corbin & Strauss, 2008, p. 104).

3.8. Limitations and Delimitations

Education in the Age of Complexity is a big topic. For this study, I narrowed in on the concrete goals of defining systems literacy and developing a theory of how systems literacy is developed to build a foundation for considering how our current K-12 curriculum does and does not serve that development. Early interviews represented an original sample that was academically and otherwise diverse. Extending some of those initial conversations with more targeted questions and increasing the sample to increase diversity improved the reliability and transferability of my findings. Some limitations were harder to resolve. For practical purposes, geographic distribution of participants was relatively limited. Though I had at least one participant in the South, one in the Southwest, one on the West Coast, and two who grew up outside of the United States, the vast majority of my participants are originally from and/or reside in New England and the Northeast. All participants were highly educated, holding master's and/or doctoral degrees. Limited diversity in geography and education level alike could introduce bias into my findings, bias that would likely be in line with my own preconceptions.

This study has made an argument for why we should reimagine the K-12 curriculum through the complexity lens, has identified what developing systems literacy could mean at this level, and has considered what impact that might have on students and society, but it has only scratched at the surface of how this work could or should play out in schools and classrooms.

3.9. Background and Role of Researcher

In any research endeavor, the questions we ask, the concepts and explanations we develop, and the theoretical and conceptual frameworks we apply to our work are reflections of our personal beliefs and understandings (Charmaz, 2000). My own background has informed every element of this study. My formal education, until recently, was primarily in the field of English. I earned my undergraduate degree at a small liberal arts college. I taught English for twelve years, earning a master's degree in my discipline over the course of five summers. I was introduced to the concept of complex systems several years ago in a course on educating for sustainability. The professor used complex systems as a lens to demonstrate how natural laws governing ecological systems can inform our understanding of manmade systems as well. Intrigued, I wanted to dig more deeply into the implications of complexity for education.

Arriving at the University of Vermont, I was introduced for the first time to the computational branches of complex systems. Here was an interdisciplinary line of study that I found both fascinating and inaccessible. To some extent, I felt illiterate, but it was clear to me that these computational methods offered alternative and powerful perspectives on the same sorts of issues that were relevant in my own fields in the humanities and social sciences. I tackled this research to gain a deeper understanding of what it means to work with, study, and explore complex systems. I wanted to know what draws the mathematician, biologist, neural network engineer, ecologist, economist, public administrator, and English teacher to this interdisciplinary field and what promise a systems approach offers in each of these disciplines and across them. To some extent, this study (and certainly the extensive memos I produced while conducting) serves as a record of my own process of becoming systems literate. As such, I have not been a neutral observer.

From the start, I was limited by my non-scientific, non-mathematical background, and I sought the feedback and critique of colleagues and participants across disciplines to accommodate that limitation. My biases came from the background I do have. Having come to systems first through the study of sustainability, I was inclined to understand all systems work as attempts to grapple with complex questions of improving equity, justice, and the state of the Earth we depend on. Throughout this study, I needed to remain open to hearing that others came to this field by other paths, with other motivations. I needed to set aside my literary and environmental lenses long enough to look through others' lenses and see the field of complex systems holistically.

3.10. Validity of Interpretation

Because of my own close connection to the subject of my study, I needed to be thoughtful and thorough in validating my interpretations. In qualitative research, "when we use the term 'validate,' we don't mean to imply that we are testing hypotheses in a quantitative sense. Validating here refers more to a checking out of interpretations with participants and against data as the research moves along" (Corbin & Strauss, 2008, p. 48). Shenton (2004) offered a series of terms to serve this purpose: *credibility* (vs. validity), *transferability* (vs. generalisability), *dependability* (vs. reliability), and *confirmability* (vs. objectivity).

To establish the credibility of a study, Shenton advocated for clearly describing the background, biases, and qualifications of the researcher and presenting findings in the light of previous research. Furthermore, he argued, the researcher should welcome "opportunities for scrutiny of the project by colleagues, peers and academics" (p. 67). Conducting this study over an extended period of time within the structure of a doctoral program provided me with many opportunities to solicit such feedback from colleagues, mentors, and peers (including presenting preliminary findings at an academic conference), further establishing the credibility of my work along the way.

So that the reader might assess the transferability of research findings for himself, Shenton argued, the researcher should provide information on a series of issues: participant information, including the number of participants, basic information about the group, the number of organizations from which participants were drawn, and any restrictions determining the type of people consulted; and data collection methods. Establishing transferability does not require that data from every instance confirm data from every other. In line with philosophies underpinning grounded theory, Shenton emphasized the need to analyze variations as reflections of multiple realities and diverse contexts. Throughout this study, I was explicit in descriptions of my participant group, recruitment parameters, and research methods so that my readers may accurately assess the transferability of my findings.

A researcher can establish the dependability of his or work by clearly describing methodological decisions including research design and implementation, details of data gathering and analysis, and reflective practice around the research process undertaken (Shenton, 2004). To establish confirmability, she must take steps to ensure that findings are grounded in data rather than her own "characteristics and preferences" (p. 72). Furthermore, Shenton recommended developing a *theoretical* "audit trail" tracking the "the manner in which the concepts inherent in the research question gave rise to the work to follow" (p. 72). I presented an abbreviated audit trail for this study in the sections on phases one and two and theoretical sampling above. Table 3.4 below offers specific details regarding my process for collecting data and checking my interpretations against existing literature and participants' feedback.

At various points in this study, I received feedback from thirteen different participants (59%), six of them (27%) more than once. Importantly, this feedback informed revisions, both for my definition of systems literacy and for my description of the process of becoming systems literate. The former, for example, I reduced from

Table 3.4

Data Collection and Member-Checking

Pseudonym	Round 1 interviews	Member-checking	Round 2 interviews	Member-checking		Round 4 interviews		Member-checking
	Exploratory research	*Checking interpretations - preliminary findings*	*Identifying skills and dispositions for grappling with complex systems*	*Checking interpretations (skills and dispositions for grappling with complex systems)*	*	*Checking definition of systems literacy, collecting data on becoming literate*	**	*Checking definition of systems literacy and/or theory of becoming literate*
Ben	✓	✓						✓
Charlotte	✓	✓						✓
Nick	✓	✓						✓
Alex			✓	✓				
Daniel			✓					
Dawn			✓					
Emmett			✓					
Ethan			✓	✓				
Gavin			✓	✓				✓
Henry			✓					
Jake			✓	✓				
Madeline			✓					
Matt			✓					✓
Max			✓	✓				✓
Noah			✓					
Oliver			✓					
Simon			✓					
William			✓					
Beth						✓		
Bob						✓		
Elizabeth						✓		✓
Genevieve						✓		

* Round 3 literature analysis: *Connecting participant data to texts and resources delineating systems skills and knowledge*

** Round 5 literature analysis: *Connecting participant data to texts describing authors' experiences with complexity*

twelve components to ten and revised to include stronger action verbs. The latter originally underemphasized the role of nonacademic learning experiences and inadvertently communicated a process of becoming that was more linear than my data supported or I understood it to be. I revised these elements and others like them accordingly.

3.11. Results, Interpretations, and Implications

Chapter four presents study results in the form of three journal articles. The first, "Systems Literacy in Three Dimensions: Cultural, Operational, and Critical Literacies for Living in a Complex World," answers the question *What is systems literacy?* The second, "Becoming Systems Literate," tackles my second research question, presenting a grounded theory describing an iterative process of becoming. The third article, "Photomosaic Possibilities: Developing a Systems Lens to Inform Curricular Redesign," argues that before schools can develop students' systems literacies in a comprehensive or cohesive way, we must develop a systems lens among teachers and school leaders.

Chapter 4: Three Journal Articles

Systems literacy in three dimensions: Cultural, operational, and critical competencies for living in a complex world

In the 21st century, transdisciplinary approaches to research and problem solving rooted in complexity theories and complex systems methodologies offer hope for understanding and solving previously intractable problems. But the knowledge and skills essential to such problem solving are too often absent from our collective practice. If modern society is to deal effectively with interconnected challenges across ecological, social, political, and economic systems, our education system must prepare students to grapple with complexity. We must educate systems literate citizens. But what does it mean to be systems literate? This article presents findings from a grounded theory study of complex systems knowledge, skills, and dispositions to contribute to a growing body of systems education literature. The study incorporates data from texts and online resources by established systems thinkers along with interviews with scholars and educators employing complexity concepts in their work across a range of academic disciplines, and it employs the *Literacy in 3D* model to frame a working definition of *systems literacy* in terms of its cultural, operational, and critical dimensions (Green & Beavis, 2012).

Keywords: Complexity, grounded theory, systems literacy, education

Education in the Age of Complexity

Since the mid-twentieth century, systems thinking, system dynamics, and complex systems sciences—diverse but related modes of inquiry—have offered new mindsets and methods for studying the world and new possibilities for addressing old problems (see, e.g., Ackoff, 1997; Alperovitz, Speth, & Guinan, 2015; Conklin, 2009; Dias, 2015; Doll, 1989; Wessels, 2006). Today, scholars and professionals in scientific fields ranging from biology and ecology to physics, math, and engineering explore complexity in their respective disciplines, and over time the boundaries of those disciplines have started to blur (Ackoff, 1997; Forrester, 2007; Mitchell, 2009; Montuori, 2015). In the humanities and social sciences, the modern explosion of big data and the computational capacity of personal computers have provided opportunities for researchers to take on quantitative aspects of questions they could answer only theoretically in times past (Byrne, 2014). Knowledge of the structures and dynamics of biological and ecological systems in particular, have come to inform our understandings of how manmade systems—political, social, technological, economic, even linguistic systems—work, interact, and change over time (Bar-Yam, Ramalingam, Burlingame, & Ogata, 2004; Meadows & Wright, 2008; Mitchell, 2009). Collectively, these innovations and insights represent deep understandings of the interdependent complex systems that constitute our world and a transition from a mechanistic, linear worldview to a new, complexity-informed paradigm (Ackoff, 1997; Dias, 2015; Doll, 1989; Forrester, 2007; Marshall, 2006; Meadows, 1999; Mitchell, 2009; Wessels, 2006). And yet, these modern understandings are too often absent from our collective practice.

In a keynote address at the Relating Systems Thinking and Design Symposium in Oslo, Norway, Dubberly (2014) discussed modern leaders' inability to design effective solutions to systems problems. "Decision makers 'not knowing what they are doing,' lacking 'adequate basis to judge effects,' is not stupidity," he said. "It's a type of illiteracy. It is a symptom that something is missing in public discourse, in organizations and businesses, and in our schools" (p. 2). That *something* is a deep understanding of complex systems. Dubberly argued, "We need systems literacy—in decision makers and in the general public" (p. 2). He closed his talk with this assertion:

> If we acknowledge that almost all the challenges that really matter—and most of the opportunities for social and economic innovation—involve systems, and if we know that we have available to us tools to help us think about systems, then we must put those tools into circulation. We must build systems literacy. To not do so would be irresponsible. (p. 10)

This study embraces that sense of shared responsibility. In an age of growing inequity, increasing racial tension, political inaction, international conflict, environmental destruction, and climate change, our schools have a central role to play in educating *systems literate* citizens, students who understand the fundamentals of complex systems across disciplinary boundaries and identify themselves as active agents in the evolution of their world (Banathy & Rowland, 2004; Edelstein, 2011). But if schools are to tackle this work in a cohesive way, educators first need a clear understanding of the concept of systems literacy and a working understanding of how one becomes systems literate.

Through an extended grounded theory study incorporating data from texts and resources developed by and interviews with complexity scholars and educators, this study has answered two questions: (1) What is systems literacy? and (2) How does one become systems literate? This article presents a working definition in response to the first question. A subsequent article answers the second.

Systems Education

Various authors have promoted the idea of rethinking the curriculum (at levels ranging from preschool to graduate school) through a systems lens (e.g., Betts, 1992; Cassell & Nelson, 2010; Dias, 2015; Fisher, 2011; Forrester, 2009; Grauwin, et al., 2012; Metz, 2012; Plate & Monroe, 2014; Senge, 2000, 2012; Sung et al., 2003; Sweeney & Sterman, 2000, 2007). A few have begun the work of defining systems literacy. Sweeney described it briefly as "an applied understanding of living systems" (in Bennett & Sweeney, n.d.). "To be literate," she explained, "means to have a well-educated understanding of a particular subject, like a foreign language or mathematics" (Sweeney, 2014, p. 3). She went on to say,

> In many fields, the knowledge must be both comprehensive and abundant enough that you are capable of putting it to use. Systems literacy represents that level of knowledge about complex interrelationships. It combines *conceptual knowledge* (knowledge of system principles and behaviors) and *reasoning skills* (for example, the ability to see situations in wider contexts, see multiple levels of perspective within a system, trace complex interrelationships, look for endogenous or 'within system' influences, have

> awareness of changing behavior over time, and recognize recurring patterns that exist within a wide variety of systems). (p. 4)

Dubberly (2014) conceptualized systems literacy in terms of a particular vocabulary along with the dual processes of *reading systems* (recognizing common patterns in diverse contexts) and *writing systems* (communicating system structures and processes to others). Furthermore, he argued, systems literacy can be rooted in a literary canon, a series of "key works of theory and criticism"; an historical context, a timeline of key players and the ideas that have moved the field forward; and a rich series of connections, "conversations among and between disciplines" (p. 3).

This study expands upon these existing definitions in three ways, (1) by employing Green's *Literacy in 3D* model to explore the cultural, operational, and critical dimensions of systems literacy (Green & Beavis, 2012); (2) by synthesizing a series of existing lists and resources delineating knowledge, skills, and dispositions related to systems thinking and system dynamics education; and (3) by engaging in conversations with systems scholars and educators to explore what it means to be literate in complex systems across a wide range of related fields. The following sections describe the conceptual framework and research design that structured this study before presenting findings in the form of ten competencies which together comprise systems literacy defined in terms of three interdependent dimensions.

Conceptual Framework: The 3D Model

The *Literacy in 3D* model identifies subject-specific literacy as "the particular literacy, or set of literacy competencies, that is inextricably part of the operation of specific subject areas as contexts for learning and meaning" (Green, 2012, p. 3). The model emphasizes production over consumption of knowledge and writing (a particularly active form of learning) over reading alone. Green posited that *thinking* and *meaning* (both verbs) can be seen as "the real 'basics'" of literacy (p. 4). He defined literacy across three overlapping dimensions: the cultural, operational, and critical.

The cultural dimension involves the terms and conventions that constitute the language of subject-specific communication. Becoming culturally literate requires one to be steeped in the context of a particular set of knowledge and experiences. Enculturation into the language and conventions of a subject is necessary for one to develop competency in using that language "as a resource for meaning" (Green, 2012, p. 5). But Green's model makes a series of important assumptions about knowledge: it is socially constructed, selected, and classified; it is taught both explicitly and implicitly; and in schools the organization of knowledge into distinct disciplines is cultural and conventional rather than natural or inevitable (Green & Beavis, 2012).

While the cultural dimension involves language and meaning, the operational dimension is more closely linked with the ways people use language to operate effectively within subject-specific contexts. It involves the skills and abilities required to engage in subject-specific activities (Faulkner, Ocean, & Jordan, 2012). Though the original *Literacy in 3D* model emphasized traditional print-based forms of reading and writing, modern interpretations have expanded the model to address communication more generally (Green & Beavis, 2012). Competency in the operational dimension is a measure of one's ability to communicate appropriately and adequately across a range of contexts (Green, 2012). The operational dimension is not only an element of literacy to be developed; it also becomes a means for further learning. Green articulated this by distinguishing between *learning literacy* and *learning through literacy*:

> The first involves the development of reading and writing abilities, or literacy capability—how children become (more) literate. The second concerns the notion of literacy as a specific tool for learning. On the one hand, literacy is conceived as the goal of schooling; on the other, it is the means of schooling. (p. 11)

While the cultural and operational dimensions of literacy offer one "access to the meaning system of the culture" and the potential to "function in it effectively and productively" (p. 7), the critical dimension emphasizes the fact that such meaning systems are not neutral. As Green explained,

> Unless individuals are also given access to the grounds for selection and the principles of interpretation (and hence given more critical insight into the processes and possibilities of knowledge production, their own and that of the culture), they are merely socialised into the dominant meaning system and lack the capacity to take an active role in its transformation. (p. 7)

The critical dimension of literacy empowers individuals to question accepted truths. As such, it must be a deeply important aspect of any literacy defined for education in changing times. The three dimensional approach to literacy involves not only teaching the commonly accepted knowledge and skills central to any particular field but also teaching learners how engage in informed, personal meaning making and contribute to an evolving body of accepted knowledge, thus contributing to both "the maintenance and transformation of culture" (p. 7-8).

Over the past few decades, Green's model has been applied to evolving forms of literacy in information technology, media literacy, and numeracy and has been employed in the contexts of pedagogy, teacher training, and research (Green & Beavis, 2012). The model's three interdependent dimensions provide a concrete framework for conceptualizing subject-specific literacies. Taken together, the operational emphasis on communication and skills, the cultural emphasis on subject-specific language and meaning, and the critical emphasis on the creative, transformative potential of active learning serve to frame a robust definition of systems literacy.

Research Design

This article presents one slice of a larger study employing grounded theory methods to explore the concept of systems literacy. To answer the question *What is systems literacy?* I analyzed data from texts and online resources delineating a range of systems skills and knowledge as presented by systems thinkers and educators along with interviews with twenty-two academics and educators conducting research in and/or teaching complex systems concepts at the middle school, high school, college, and/or graduate level. (See Table 1: Text-Based Data Sources and Table 2: Participants below.)

Author	Text	Year	Domain
Dubberly	"A Systems Literacy Manifesto"	2014	Software design
	Snapshot of concepts: "Systems vocabulary . . . systems reading skills . . . systems writing skills . . . the literature of systems . . . the history of systems . . . connections [between systems, disciplines, domains, and methods]" (n.p.)		
Plate & Monroe	"A Structure for Assessing Systems Thinking."	2014	Systems thinking and system dynamics education
	Snapshot of concepts: "Recognizing interconnections . . . identifying feedback . . . understanding systems at different scales . . . differentiating types of stocks and flows . . . understanding dynamic behavior . . . creating simulation models . . . incorporating systems thinking into policies" (p. 4-6)		
Richmond	"Systems Thinking: Critical Thinking Skills for the 1990s and Beyond"	1993	Systems thinking and system dynamics education
	Snapshot of concepts: "Dynamic thinking . . . closed-loop thinking . . . generic thinking . . . structural thinking . . . operational thinking . . . continuum thinking . . . scientific thinking . . . educational process . . . thinking paradigm . . . learning tools" (p. 114-131)		
Sweeney	"12 Habits of Mind"	(n.d.)	Systems thinking and system dynamics education
	Snapshot of concepts: "Sees the whole . . . looks for connections . . . pays attention to boundaries . . . changes perspective . . . looks for stocks . . . challenges mental models . . . anticipates unintended consequences . . . looks for change over time . . . sees self as part of the system . . . embraces ambiguity . . . finds leverage . . . watches for win/lose attitudes" (n.p.)		
Waters Foundation	"Habits of a Systems Thinker"	2014	Systems thinking education
	Snapshot of concepts: "Seeks to understand the big picture . . . observes how elements within systems change over time . . . recognizes that a system's structure generates its behavior . . . identifies the circular nature of complex cause and effect relationships . . . makes meaningful connections within and between systems . . . changes perspectives to increase understanding . . . surfaces and tests assumptions . . . considers an issue fully and resists the urge to come to a quick conclusion . . . considers how mental models affect current reality and the future . . . uses understanding of system structure to identify possible leverage actions . . . considers short-term, long-term and unintended consequences of actions . . . pays attention to accumulations and their rates of change . . . recognizes the impact of time delays when exploring cause and effect relationships . . . checks results and changes actions if needed: 'successive approximation'" (n.p.)		

Table 1: Text-Based Data Sources

Participants, identified by pseudonyms throughout this study, were selected through a combination of theory-based and theoretical sampling (Patton, 2002). All incorporate systems thinking, system dynamics, and/or some form of complexity theory or complexity informed methods in their work. They include sixteen professors teaching at the undergraduate and graduate levels across a range of disciplines from math, statistics, and computer science, to archeology, environmental studies, and public administration. Additionally, they include three providers of professional development for K-12 and college educators and three middle and high school teachers of social studies, science, sustainability, and food systems. Participants were drawn from twelve institutions including seven colleges and universities (five private, two public), three middle/high schools (one private, two public), and two professional development organizations. They include six women and sixteen men ranging in age from their early thirties to early seventies. Engaging a diverse set of participants was essential for identifying both common patterns and variations in concepts emerging from the data (Corbin & Strauss, 2008).

Pseudonym	Profession	Department/Domain
Alex	Professor	Mathematics and Statistics
Ben	Middle/high school teacher	Science
Beth	Professional developer	K-12 Education
Bob	Professor	Classics
Charlotte	Professor	Computer Science
Daniel	Professor	Public Administration and Policy
Dawn	Professor	School of Engineering
Elizabeth	Educator	K-12 and Teacher Education
Emmett	Professor	Communication Management and Design
Ethan	Professor	Anthropology and Archaeology
Gavin	High school teacher	Social Studies
Genevieve	Professional developer	K-12 Education
Henry	Professor	Public Administration and Policy
Jake	Professor	Environmental Studies and Sciences
Madeline	Professor	Biochemical Engineering
Matt	Professor	Electrical Engineering
Max	High school teacher	Science and Food Systems
Nick	Professor	Comm. Development and Applied Economics
Noah	Professor	Political Science
Oliver	Professor	Information Technology
Simon	Professor and dean	Environmental Humanities
William	Professor	Mathematics and Statistics

Table 2: Participants

Throughout the extended study conducted over the course of two years, I welcomed opportunities to verify the credibility and transferability of my findings (Shenton, 2004). The first article to come out of this study presented preliminary findings in the form of nine skills and dispositions for grappling with complexity. I shared those findings with seven of the original eighteen participants for member checking (Creswell, 2013) before presenting that paper in a roundtable session on complexity in education at a meeting of a national research association. In a subsequent research cycle, I used the *Literacy in 3D* model to reanalyze those eighteen interviews along with the five text-based resources identified above. I then presented my emerging definition of systems literacy to four new participants. Their feedback and additional insights informed revisions. I returned to six of my original participants for a final round of member checking. The iterative nature of this study, cycling between data collection, data analysis, and returning to the literature has helped to ensure that my findings are empirically grounded (Corbin & Strauss, 2008; Linden, 2006; Toscano, 2006). In the following sections I present the working definition of systems literacy that emerged.

Defining Systems Literacy

Systems literacy is multi-faceted. Table 3 below (adapted from a similar graphic presented in Green & Beavis, 2012), presents the definition as a series of interrelated and overlapping components. These components are organized in terms of the cultural, operational, and critical dimensions (see labels on the far left of the table). Check marks of various sizes in the right hand columns demonstrate overlap between the dimensions. In systems literacy, as in other specific subjects where the *Literacy in 3D* model has been employed, the divisions between the cultural, operational, and critical dimensions are somewhat artificial. Though it is useful to delineate the three, it is important to recognize that they function simultaneously rather than hierarchically (Green, 2012). Visual representations inevitably fall short in communicating the interconnected nature of the three dimensions. And yet, it is the simplifying role of tables and graphics that makes them useful.

The Cultural Dimension

The cultural dimension of systems literacy connects with content knowledge and conventions, specifically, the context and language of complexity. This meaning system is not set in stone. Having emerged across a wide range of disciplines, it has not been canonized as a whole. It continues to evolve. And yet, there are a history and body of literature to be explored, and from these sources, foundational language and knowledge of complexity form a systems lens through which literate individuals, to use Freire's phrase, "read the world" (Freire, 1985). Byrne and Callaghan (2014) referred to this lens as the "complexity frame of reference." Capra and Luisi (2014) called it a "systems view of life." Whatever it is called, the systems lens is at the heart of the cultural dimension of systems literacy. Components 1.1, 1.2, and 1.3 below articulate some important properties of and variations within that cultural dimension. Names attached to particular quotes refer to study participants (see Table 2 above).

1.1 Systems literate individuals know the context and language of complex systems stemming from at least one branch of complexity studies (e.g., complexity theories, systems thinking/system dynamics, computational complex systems methods as in agent-based modeling or network analysis, etc.). Through a quantitative analysis of journal articles published on the theme of complexity in STEM fields, Grauwin et al. (2012) made the case that there is not a single systems theory, nor "a collection of theoretical books or articles revealing the 'universal' explanation" (p. 1,336). Extending beyond STEM fields to interview participants across a wider range of disciplines, I have found that the point holds true. Participants drew distinctions between systems thinkers who build formal simulation models and those who don't. Among those who do, participants distinguished between modelers who "study things in aggregate," lumping individuals together in populations, and those who "want to track individuals" (Henry).

	Systems literate individuals . . .	CULTURAL (Meaning, knowledge)	OPERATIONAL (Communication, skills)	CRITICAL (Power, dispositions)
CULTURAL	**(1.1) know the context and language of complex systems** stemming from at least one branch of complexity studies (e.g., complexity theories, systems thinking/system dynamics, complex systems computational methods, etc.)	✔	✓	✓
	(1.2) read the world through a systems lens, actively employing systems thinking and/or a complexity frame of reference to see connections between parts and wholes, between diverse subjects and ideas, and between common patterns across contexts	✔		✓
	(1.3) comprehend self-organization and emergence, understanding how nestedness, interdependence, and scale impact adaptation, evolution, and emergent properties	✔		✓
OPERATIONAL	**(2.1) cross disciplinary boundaries**, using knowledge about systems to enhance domain specific knowledge and skills (e.g., knowledge and skills in math, computing, data analysis, design, policy work, etc.), and vice versa	✓	✔	✓
	(2.2) employ scientific inquiry and empirical methods to understand reality, emphasizing both structure and agency, remaining open to new and contradictory information, and embracing ambiguity and uncertainty		✔	✓
	(2.3) work to understand nonlinear change, looking beyond simple cause-effect relationships to identify underlying variables and patterns of change over time, anticipate unintended consequences, identify points of leverage, and design effective solutions	✓	✔	✓
	(2.4) activate multiple modes of communication (which may include the creation of computer simulations, graphic illustrations, written descriptions, etc.) throughout the learning process to structure thinking and construct and share knowledge and understanding		✔	
CRITICAL	**(3.1) pursue multiple perspectives** in a given situation to avoid polarized or dichotomous thinking and increase personal and collective understanding	✓	✓	✔
	(3.2) recognize the power of mental models and challenge assumptions and heuristics that limit one's ability to align understanding with empirical evidence	✓		✔
	(3.3) engage in active, adaptive learning to develop skills required for new situations and to make meaning out of new information		✓	✔

Table 3: Components of Systems Literacy

Some spoke of a wider range of modeling approaches, referring to complex systems as an umbrella term classifying "tools to tackle analyzing systems that have a great deal of complexity" (Dawn). Some participants spoke of complexity as an explicitly mathematical field of study. Others discussed it in the contexts of social science research and project management.

Daniel emphasized that the differences between the branches of complexity studies matter. "It's important," he said, "to get it straight and to think clearly and precisely about it." For the purpose of building a working definition of systems literacy, though, it is helpful to focus less on the differences between branches and more on the common concepts and themes across them, to see them all as particular ways of working within a common paradigm. Some terms that came up repeatedly included *systems* (e.g., linear vs. nonlinear, simple vs. complicated vs. complex, manmade vs. natural); *reinforcing* and *balancing feedback*; *nestedness*, *self-organization*, and *emergence*; *cycles*, *diversity*, and *interdependence*. A systems vocabulary paired with contextual knowledge from the literature of complexity studies serves as an access point to understanding complexity in the world.

1.2 Systems literate individuals read the world through a systems lens. Charlotte explained how this lens helps her to "frame a problem" and "make further connections." Jake cited author Derek Cabrera when he talked about reading the world in terms of systems, being concrete in delineating system boundaries, clear about relationships, and careful to consider the structure and function of a system from multiple perspectives (see Cabrera & Cabrera, 2015). Max made the point that "everything we're dealing with is systems. Recognizing the elements, identifying the interconnections, identifying feedback, and analyzing the behavior of a system from that perspective," he said, "is essential."

Participants discussed how this frame of reference applied to and informed their own research, and several described teaching students how to see through a systems lens. Gavin explained how the systems perspective helps students tie disparate ideas together. "Everything is related," he said, "Everything is connected, but when you can show that what someone is being asked to learn . . . is connected, is meaningful, then all of a sudden, they're going to see more value, and they're going to be more engaged in what they're doing." This concept is consistent in the literature. A systems thinker "makes meaningful connections within and between systems" (Waters Foundation, 2014, n.p.), "looks for interdependencies" (Sweeney & Meadows, 2010, p. 2), "assumes that nothing stands in isolation; and so tends to look for connections among nature, ourselves, people, problems, and events" (Sweeney, n.d., n.p.). Participants emphasized this with statements like, "The world that we live in is kind of interconnected. And if we're not smart enough to see those connections, then we can make big mistakes" (Daniel).

1.3 Systems literate individuals comprehend self-organization and emergence. It is common within complexity studies to say that a system is more than the sum of its parts. Bob pushed this concept further, drawing on a reference to gestalt philosopher Kurt Koffka. A system, he explained, isn't *more* than the sum of its parts, it is something entirely *other* (see Koffka, 2013; also Anderson, 1972). It is this *other* thing that complexity scholars aim to make sense of. Matt put this in historical context: "Through the Enlightenment, you had tremendous success in understanding smaller and smaller pieces of the universe until we had pretty good models for all the pieces, and then you try to zoom out and you realize . . . the universe still doesn't make any sense."

Understanding systems whole, synthesizing parts and wholes, requires both specialists (domain experts) and generalists (connectors). Ben explained, "We will always need specialists. We also need some people that are able to piece together the whole picture. . . . That's where systems science and complex systems come in." The big picture and the details work together. The parts and their relationships together tell the whole story. Emphasizing relationships in terms of self-organization and emergent properties is central to comprehending the world as a series of interconnected, interdependent, and perpetually evolving complex systems (Wessels, 2006).

The Operational Dimension

The operational dimension of systems literacy emphasizes the skills used for developing and sharing understandings about the complex nature of the world. Systems literate individuals, often interested in solving real-world problems, are pragmatic in their approaches to understanding how the world works. Typically, this requires them to cross disciplinary divides. They ask questions, avoid jumping to conclusions, and embrace uncertainty and ambiguity (Sweeney, n.d.; Waters Foundation, 2014). They are particularly interested in how things change over time (Plate & Monroe, 2014; Sweeney, n.d.; Waters Foundation, 2014). And they employ multimodal communication skills both to build and to convey understanding. Components 2.1-2.4 together constitute the operational dimension of systems literacy.

2.1 Systems literate individuals cross disciplinary boundaries. Much systems knowledge is rooted in math (as in chaos and complexity theories) and science (especially biology, ecology, and physics). Charlotte was not alone in describing a "love of science" as central to her own educational path and a diverse math/science background as foundational for working with systems. However, because natural and manmade systems do not adhere to the socially constructed divisions between disciplines, complexity is inherently inter- and transdisciplinary.[1] Alex argued, "The best scientific problems, the ones that are interesting . . . are really at the intersection of lots of different disciplines."

Participants described using knowledge about systems to enhance domain specific knowledge and skills (e.g., knowledge and skills in math, computing, data analysis, design, policy work, etc.), and vice versa. Oliver, Max, and Dawn discussed using a systems lens to operationalize the concept of sustainability. Simon, a college dean, described being drawn to existing natural processes and systems as models for institutional organizing structures. Other participants discussed applying complexity concepts and computational skills to the fields of biology, genetics, robotics, and power systems, among others. Dawn explained, "I think the field of complex systems is one of the few that truly can be transdisciplinary, because it's just a tool for helping people who already care about whatever complexity that they care about."

Participants discussed not only an interest in bridging disciplinary divides (especially by improving communication and increasing common language between them), but sometimes even a frustration with the fact that such barriers exist. As educators, some spoke of actively breaking down the divides for their students. Emmett described designing learning opportunities to help students "bring the modes of thinking from, say, philosophy and politics and design and research together." Max said of his sustainability curriculum, "The immediate goal for me is having greater cross disciplinary connections. You know I've been using this theme of sustainability and specifically the food system as a vehicle to do that, and this systems thinking is now just another kind of tool to integrate, to make these cross disciplinary connections."

2.2 Systems literate individuals employ scientific inquiry and empirical evidence to understand reality. Richmond (1993) identified *operational thinking* as a core critical systems thinking skill. "Thinking operationally means thinking in terms of how things really work—not how they theoretically work, or how one might fashion a bit of algebra capable of generating realistic-looking output" (p. 127). Refusing to oversimplify reality, many participants identified the need to embrace ambiguity and uncertainty, emphasize both structure and agency, and remain open to new and contradictory information. Several spoke of the process of scientific inquiry and scientific rigor. Dawn described such inquiry in the context of ecology and engineering, explaining that it isn't necessarily about setting up a hypothesis or experimental design in the lab. Rather, it is about learning about real systems as they function nested within other real systems. As Ethan said, "Life is messy. The world is messy. People are messy."

Many participants talked about math, computers, and computational models as powerful tools for unpacking that messiness. Modeling data (in some cases, millions of data points a day), explained Alex, "will tell you things you might not know from sort of a close read of a particular book, right?" Computers, of course, are central to this work. William discussed the role of algorithms in sorting out big networks of interconnected things, looking for structure, and making meaning out of data. "It's difficult and sort of a hard thing to analyze," he said, "but it's clearly what we have to do to reflect the real world." Dawn, Henry, and Oliver all spoke of the power of simulation models to surface unexpected realities and challenge preconceived notions about how a system might play out over time. Henry described the difference between thinking systemically and modeling systems.

> Most of us would not get surprises out of drawing word and arrow diagrams with boxes around stocks. But we do get surprises when we quantify some of those things and we simulate and, son of a gun, the model didn't do what we quite thought it was going to do when we change that parameter, and then we go figure out why.

2.3 Systems literate individuals work to understand nonlinear change. They look beyond simple cause-effect relationships to identify patterns of change over time and anticipate unintended consequences (Plate & Monroe, 2014; Richmond, 1993, Sweeney, n.d.; Waters Foundation, 2014). Writers in the system dynamics tradition emphasized the structure of change in terms of stocks, rates of change, and the impact of feedback delays (Plate & Monroe, 2014; Sweeney, n.d.; Waters Foundation, 2014). Sweeney (n.d.)

explained that a systems thinker “knows that hidden accumulations (of knowledge, carbon dioxide, debt, and so on) can create delays and inertia” (n.p.). Oliver discussed this in the context of project management and working with clients to surface “how effects accumulate over time. . . . One of the things about systems and emergent behavior that’s really interesting,” he said, “is that you might think things are going along just fine, but a combination of accumulated events could be seen as a precursor to a catastrophic situation.”

In complex systems, cause and effect are interdependent constructs. Systems authors and study participants alike tended to describe change as cyclical (Plate & Monroe, 2014; Richmond, 1993; Waters Foundation, 2014). Ethan spoke about cycles of the building up and falling apart of social and political systems as evidenced in the archeological record, and he discussed political, economic, and cultural factors that can render societies particularly unstable and prone to precipitous change. Noah connected the study of change over time to mental models in political science: “We like to think about authoritarian systems as kind of everybody just staying in lockstep and that there’s no space to do anything differently or something to that effect,” he said. “I think that really underestimates the creative capacity of agents and actors to kind of creatively adapt to their situation.”

The emphasis on agency and the related concept of endogeneity, discussed by several participants, connects to the systems understanding of “‘within system’ influences” on change (Sweeney, 2014, p. 3). In the social sciences it is common for researchers to model change in terms of causal factors outside of the system (a concept known as *exogeneity*). Noah explained, “The reason we can’t model [causes] in an exogenous way is because they are in fact endogenous. There’s something liberating about just recognizing that . . . is a fact of social systems and moving beyond it, right, and trying to understand what the kind of different causal pathways are.” Noah described endogeneity as a liberating concept. Henry described it as empowering. Daniel explained, from a systems perspective, “I’m not a victim of bad things that happen to me. I kind of realize that I’m shaping the world that I live in.” From a systems perspective, one must grapple with both nonlinearity and endogeneity in order to identify points of leverage (Meadows, 1999), design solutions, and participate in change.

2.4 Systems literate individuals activate multiple modes of communication (which may include the creation of computer simulations, graphic illustrations, written descriptions, etc.) to construct and share knowledge and understanding. Byrne and Callaghan (2014) emphasized the power of narrative for understanding “the past history, current condition and future potential of complex systems” (p. 11). Some participants echoed this sentiment. Max talked about storytelling in terms of unfolding a model to communicate “how a system works.” He discussed both traditional writing formats and new modeling approaches as different ways students could convey their understanding. Noah argued for a mixed methods approach to research and writing about complexity. “Methodologically different approaches allow you to kind of get at different types of processes,” and the various approaches are more effective, he argued, when they work together. “Your analytic narrative is more persuasive,” he said, “when you can draw on . . . baseline data.”

Dubberly (2014) described systems *writing* skills as “skills of synthesis, for understanding and describing existing systems and for imagining and describing new systems” (p. 3). Communication, as a component of systems literacy, is an active, creative process of describing, explaining, and understanding existing systems but also generating new ideas, designs, and solutions. Emmett discussed the visual portrayal of knowledge and modeling through words. Henry described using pictures and graphs to think about interconnections among the elements of a complex system. Max discussed how the need to choose language and units precisely in modeling forces his students to clarify their thinking. Dawn, an environmental engineer, discussed experiences using filmmaking to communicate scientific findings to a lay audience. The operational dimension of literacy is largely about using communication to generate and share meaning. The aim in any situation must be to communicate in whatever way is effective for the purpose and audience at hand.

Together, the operational components of systems literacy emphasize communicating across disciplinary boundaries; creating meaning through rigorous, empirically grounded inquiry; and grappling with nonlinearity in understanding and effecting change. Furthermore, they call on individuals to develop skills to maximize the potential of new and evolving communication platforms, not only to share their systems knowledge, but also to build it.

The Critical Dimension

When thinking about the critical dimension of literacy, it is helpful to associate “critical” with “critique” rather than “important.” The critical dimension asks us to critique knowledge and information, to consider *what counts* and *why* as we assess and build meaning. Systems literacy as a whole asks us to see the world differently, to question assumptions, to consider diverse perspectives, to explore possibilities. This is why Table 3 on page 71, depicts the majority of the ten components falling at least partly within the critical dimension of systems literacy. And it is why Figure 1 below depicts the critical components of systems literacy informing the cultural and operational components. The systems lens is an artifact of a new paradigm. As knowledge, meaning, and the language of complexity continue to evolve, our understandings of the world shift in response. To communicate honestly in a changing world, to act effectively in changing times, we must take a critical, creative approach. Three final components of systems literacy make up the critical dimension, not because they are the only ones infused with a critical sensibility, but because they are the ones that are most directly about the power of perspective and the empowering effect of active, adaptive learning.

3.1 Systems literate individuals recognize the power of mental models. Sweeney (n.d.) wrote that systems thinkers challenge their “own assumptions about how the world works ([their] mental models)” and look for how those models “may limit thinking” (n.p.). From the Waters Foundation (2014): Systems thinkers consider “how mental models affect current reality and the future” (n.p.). Wessels (2006) shed light on the destructive potential of mental models when he opened his book *The Myth of Progress* with this 2002 quote from George W. Bush: “Economic growth is key to environmental progress" (p. xv). An alternative mental model, of course, is that economic growth is at the root of environmental destruction. It is easy enough to imagine how either assertion, when deeply internalized, could serve as a lens through which one might read the same situation in two very different ways.

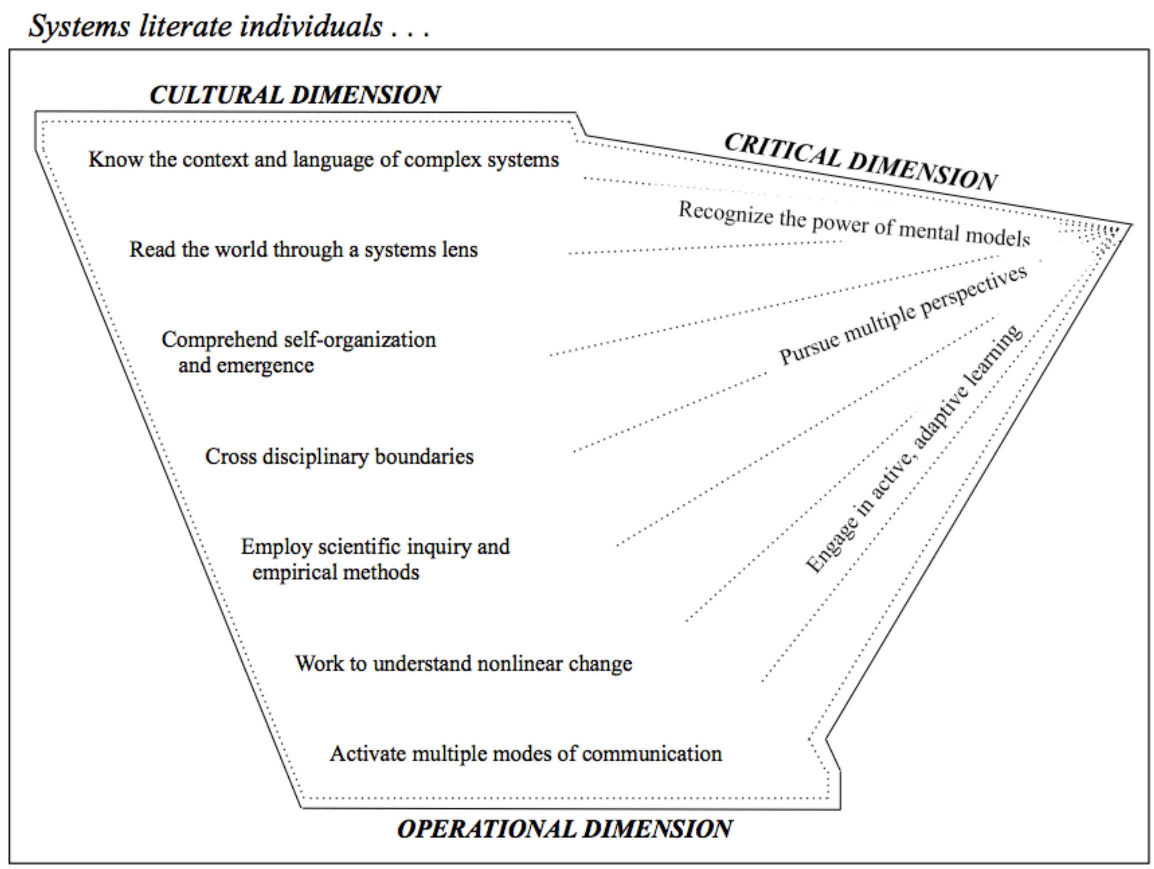

Figure 1: Interconnected Dimensions of Systems Literacy

Participants identified various other mental models that can be problematic. Ben spoke of "this rugged individualism that permeates everything we do." Dawn discussed economic assumptions around the value of consumerism. Ethan talked about an effort in anthropology to move beyond worldviews wrapped up in terms like "developed" and "undeveloped," "third world" and "first world," because they imply "that the only way to organize a society is the way that Western societies have done it." He explained that a major challenge of anthropology is to understand things that are "so different from what our experience is" in a scientifically rigorous way. Surfacing and challenging mental models is central to that work.

While Ethan spoke of actively checking mental models within the discipline of anthropology, Emmett spoke of recognizing the disciplines themselves as lenses through which we see the world. He described an interdisciplinary course he had designed in which "we get really deep into *What is your discipline? . . . What are the objects of study? What are the assumptions that are made? What are the methods and how are those completely different than the person sitting next to you?"* Emmett described challenging mental models head on by asking people working across disciplinary boundaries to consider how their beliefs and assumptions differ from others' and how they can communicate across those divides.

Of course, mental models are not inherently negative. The systems lens is itself a particular mental model, and some participants spoke of teaching it explicitly. Gavin said of his ninth grade social studies classes, "We start with reminding ourselves that we generally think in a linear fashion, and we understand what a linear system is, and then we say, well complex systems is how we should be thinking." He explained that his students have "got to be willing to open their minds and think differently than they've ever thought before." Max said of his high school science students, "I want them to think in systems."

3.2 Systems literate individuals seek multiple perspectives in a given situation to avoid polarized thinking and increase personal and collective understanding. As Sweeney (n.d.) argued, "What we see depends are where we are in the system" (n.p.). Plate and Monroe (2014) described systems thinking as involving "the ability to observe a system at multiple scales. . . . the ability to zoom out and understand the system's behavior in a broad scale and then to zoom back in to understand the details" (p. 4). Big data versus case study, big picture versus detail-focus, macro- versus micro- explanatory devices, structure versus agency—each perspective offers legitimate pieces when puzzling out complex realities.

Embracing this idea, systems literate individuals find ways of shifting their own perspectives to think about the same problem or system from multiple angles (Sweeney & Meadows, 2010; Waters Foundation, 2014). Oliver expressed this concept in terms of "stakeholder complexity," which he described as "having legitimate perspectives—socially legitimate, legally legitimate, organizationally legitimate perspectives, that account for or contribute to a variety of different perspectives and possible solutions to problems." Emmett talked about the need to recognize "that what you see in the world is what you see in the world, that your lens is just as biased as anyone else's." Ben said, "You spend a lot of time and energy on anything, and you get emotionally attached to it. You stop looking at it critically and start defending it." Fully considering multiple perspectives is an antidote to such close-mindedness.

Multiple participants emphasized the concepts of empathy, connectedness, and interdependence. These concepts are particularly powerful when paired with an endogenous point of view, which Daniel described this way:

> I'm inside the system. I'm an actor in the system . . . What I do now is going to have an impact on the system, however slight, and at some future point, I or my children or someone is going to be living with the consequences of what I do or what I don't do.

Such a perspective is inherently imbued with a sense of personal agency.

3.3 Systems literate individuals engage in active, adaptive learning to make meaning out of new information. Richmond (1993) emphasized active, learner-directed learning focused on construction rather than assimilation of knowledge. "Meaning and understanding," he wrote, "are 'making processes, not 'imbibing' processes" (p. 115).

Active learning is not only the way through which one develops her systems literacy; it is also a core component of what it means to be literate. Though they emphasized it in different ways, participants in general spoke about ongoing, situational learning. Many described exploring complexity through reading, attending workshops and trainings, and enrolling in courses. Some spoke of learning systems concepts or methods collaboratively with colleagues, mentors, and coauthors. Several spoke of learning specific tools (a new algorithm or a piece of software) to tackle a particular problem or accomplish a particular task.

Active learning is an iterative process. Simon talked about the outdoor and experiential model of learning that engages students in cycles of experience and reflection as they build knowledge and understanding (see e.g., Kolb, Boyatzis, & Mainemelis, 2000). Max and Henry spoke about the iterative process of learning to build models, starting simply and returning to build in increasing levels of complexity. Several participants described a general desire to learn, to know and understand more, to ask and answer *why questions*, and to try new things. Charlotte spoke of curiosity in general and a willingness to keep asking questions.

While some participants did express a love of learning for the sake of learning, they expressed other motivators as well. Emmett talked about designing solutions. Ethan talked about adding to collective knowledge. William connected learning to change: "So we kind of know what the game is now. . . . Going forward, it's about understanding real systems that exist—natural and manmade ones—and also figuring out how to make new ones." Critical, adaptive learning creates change—change in practice, change in collective knowledge, change in systems. It also creates change in the learner. Elizabeth spoke of the tension that can exist in a complexity scholar's mind between academic and intuitive knowledge, and she spoke of the new understandings that emerge as products of that tension. "A good learner," she said, "is an adaptive being."

Summary

The field of complexity studies is vast and diverse, and it remains emergent and evolving. Green's *Literacy in 3D* model has served as a useful framework for developing a multi-dimensional explanation of what it means to be systems literate (Green & Beavis, 2012). The cultural dimension, emphasizing knowledge and meaning, accounts for the language and contexts of complexity and the role of the systems lens in reading the world. It can be characterized by a focus on interconnectedness, interdependencies, synthesis, and holism. The operational dimension details the skills and dispositions required for constructing and communicating meaning about complex systems. Individuals who are operationally literate cross disciplinary boundaries, employ scientific inquiry and empirical evidence to understand and describe reality, study nonlinear change, and activate many modes of communication to construct and convey meaning.

Systems literacy is by its nature critical in as much as it calls into question official knowledge and illuminates a non-linear, non-mechanistic paradigm. But the critical dimension, even more than the cultural or operational, is what sets this definition of systems literacy up to be dynamic. Critically literate individuals recognize the power of mental models both to support and to limit understanding. In this light it is important to recognize that seeing the world as a series of interconnected, interdependent complex systems is a particular mental model. A truly literate individual will continue to challenge the assumptions of that explanatory device. Through pursuing multiple perspectives and engaging in active, adaptive learning, she will continue to build her complex systems knowledge and skills and fine-tune her systems lens for reading the world.

The Purpose of a Systems Education

This study drew insights from scholars and educators working within and across a wide range of complexity traditions, and this broad search space yielded findings that resonate with much of what has already been written about the purpose of a systems education. Forrester (2009) argued that a systems dynamics education should,

> (1) Sharpen clarity of thought and provide a basis for improved communication, (2) Build courage for holding unconventional opinions, (3) Instill a personal philosophy that is consistent with the complex world in which we live, (4) Reveal the interrelatedness of physical and social systems, and (5) Unify knowledge and allow mobility among human activities. (p. 5)

Sweeney (2014) argued that building systems literacy will increase students' compassion for others and help children "to see themselves as part of, rather than outside of, nature" (p. 4). She wrote, "As they grow up and learn about the economy, climate, education, energy, poverty, waste, disease, war, peace, demographics, and sustainability," "children who are systems literate will tend to look at all these issues as interrelated" (p. 4).

It is unsurprising that the findings presented here confirm much of what has been written about systems education, but they also resonate with many themes alive in the broader field of education discourse. Students need to understand science and engage in scientific inquiry. They need to embrace multiple perspectives, see connections between seemingly disparate concepts, collaborate, communicate, and develop skills and dispositions to support lifelong learning. These findings echo much of what has already been said about effective educational practices in the contexts of education for sustainability, 21st century skills, and the modern standards movement (see e.g., Cloud, 2012; Jacobs, 2010; NGSS Lead States, 2013; Wagner, 2008). In doing so, they illuminate ways in which systems literacy could act as a unifying theme for drawing together diverse initiatives for education transformation. Actively and explicitly supporting students in developing a systems lens can reinforce long-established goals for education by connected them to one overarching goal—preparing systems literate citizens, creating what Weil (2012) referred to as "solutionaries" (n.p.).

Systems educators have argued that without systems skills, "we continue to operate from crisis to crisis, stuck on the problem solving treadmill, where our 'solutions' often only create more problems or make the original problem worse" (Sweeney, 2009, n.p.). If instead we can successfully develop these skills across the education system, "we will have a generation of people who will actually think differently" (Fisher, 2011, p. 406). Dias (2015) argued that systems understandings can support students in developing skills for thriving in changing times. "The imperative to prepare children with capacities to flourish in their futures," she argued, "is never more urgent than now, when change and unpredictability are fast becoming our most reliable constants" (n.p.). Developing systems literacy is about helping people to see and study the world in a new way. It is about educating in and for a new paradigm.

Note: 1. Marshall (2006) defined interdisciplinarity as "the ability to think deeply in two or more disciplines" (p. 53). "Transdisciplinary understanding," she wrote, "goes even deeper and further by embracing all the ways we come to know: knowing through disciplines, knowing across and between them, and, most important, knowing beyond disciplinary boundaries. The purpose of transdisciplinary learning is to understand the unity of knowledge by identifying principles and patterns that go beyond a single domain and are common to all of them" (p. 57).

References

Ackoff, R. L. (1997). Systems, messes and interactive planning. *The Societal Engagement of Social Science*, *3*, 417-438.

Alperovitz, G., Speth, J. G., & Guinan, J. (2015). The Next System Project: New political-economic possibilities for the 21st century. Retrieved from http://thenextsystem.org/#updates

Anderson, P.W. (1972). More is different: Broken symmetry and the nature of the hierarchical structure of science. *Science, 177*(4047), 393-396.

Banathy, B.H., & Rowland, G. (2004). *Guiding Our Evolution: If we don't do it, who will?* Retrieved from http://documents.mx/documents/guiding-our-evolution-if-we-dont-do-it-who-will.html

Bar-Yam, Y., Ramalingam, C., Burlingame, L., & Ogata, C. (2004). *Making things work: Solving complex problems in a complex world*. Cambridge, MA: NECSI, Knowledge Press.

Bennett, L. & Sweeney, L. B. (n.d.). If you cut a cow in half, do you get two cows? Center for Ecoliteracy. Retrieved from http://www.ecoliteracy.org/essays/if-you-cut-cow-half-do-you-get-two-cows

Betts, F. (1992). How systems thinking applies to education. *Educational Leadership*, *50*(3), 38–41. doi:10.1579/0044-7447

Byrne, D. (2014). Thoughts on a pedagogy of complexity. *Complicity: An International Journal of Complexity and Education, 11*(2), 40-50. Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/view/22963

Byrne, D. & Callaghan, G. (2014). *Complexity theory and the social sciences: The state of the art.* New York, NY: Routledge.

Cabrera, D., & Cabrera, L. (2015). *Systems thinking made simple: New hope for solving wicked problems*. [place of publication not indicated]: Odyssean.

Capra, F., & Luisi, P. L. (2014). *The systems view of life: A unifying vision*. Cambridge: Cambridge University Press.

Cassell, J. A., & Nelson, T. (2010). Visions lost and dreams forgotten: Environmental education, systems thinking, and possible futures in American public schools. *Teacher Education Quarterly*, *37*(4), 179-197. Retrieved from http://go.galegroup.com/ps/i.do?id=GALE%7CA246449260&v=2.1&u=vol_b92b

&it=r&p=ITOF&sw=w
Cloud, J. P., ed. (2012). Education for sustainability: EfS standards and performance indicators. The Cloud Institute for Sustainability Education. Retrieved from http://cloudinstitute.org/cloud-efs-standards/
Conklin, J. (2009). *Building shared understanding of wicked problems*. Interview with Christensen, K. *Rotman Magazine*. Retrieved from http:// www.cognexus.org/Rotman-interview_SharedUnderstanding.pdf
Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Los Angeles, CA: Sage Publications.
Creswell, J. W. (2013). Qualitative inquiry and research design: Choosing among five traditions (3rd ed.). Thousand Oaks, CA: Sage Publications.
Dias, S. (2015). Imagination and complexity: Creative-adaptive capacity for teaching and learning in the 21st century. Proceedings from AERA '15: American Educational Research Association. Chicago, IL.
Doll, W. E. (1989). Complexity in the classroom. *Educational Leadership*, *47*(1), 65-70.
Dubberly, H. (2014). A systems literacy manifesto. In *Proceedings of RSD3, Third Symposium of Relating Systems Thinking to Design*. Oslo, Norway: Oslo School of Architecture and Design, October 15-17, 2014. Retrieved from http://systemic-design.net/wp-content/uploads/2014/08/Hugh_Dubberly_systems_manifesto.pdf
Edelstein, W. (2011). Education for Democracy: reasons and strategies. *European Journal of Education*, *46*(1), 127–137 doi:10.1111/j.1465-3435.2010.01463.x
Faulkner, J., Ocean, J., & Jordan, K. (2012). Designing multiliteracies in 3D. In Green, B. & Beavis, C. (Eds.), *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.
Fisher, D. M. (2011). "Everybody thinking differently": K–12 is a leverage point. *System Dynamics Review*, *27*(4), 394–411. doi:10.1002/sdr.473
Forrester, J. W. (2007). System dynamics—a personal view of the first fifty years. *System Dynamics Review*, *23*(2-3), 345–358. doi:10.1002/sdr.382
Forrester, J. W. (2009). Learning through system dynamics as preparation for the 21st century. Sloan School of Management. Massachusetts Institute of Technology. Retrieved from http://www.clexchange.org/curriculum/complexsystems/complexsystems_resources.asp
Freire, P. (1985). Reading the world and reading the word: An interview with Paulo Freire. *Language Arts*, *62*(1), 15–21. Retrieved from http://www.jstor.org/stable/41405241
Grauwin, S., Beslon, G., Fleury, É., Franceschelli, S., Robardet, C., Rouquier, J.-B., & Jensen, P. (2012). Complex systems science: Dreams of universality, interdisciplinarity reality. *Journal of the American Society for Information Science and Technology*, *63*(7), 1327–1338. doi:10.1002/asi.22644
Green, B. (2012). Subject-specific literacy and school learning: A revised account. In Green, B. & Beavis, C. (Eds.), *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.
Green, B., & Beavis, C. (2012). *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Jacobs, H. H., & Association for Supervision and Curriculum Development. (2010). *Curriculum 21: Essential education for a changing world*. Alexandria, VA: Association for Supervision and Curriculum Development.

Koffka, K. (2013). *Principles of gestalt psychology.* Routledge. Retrieved from https://books.google.com/books?id=tWxHAQAAQBAJ&dq=koffka+other+more&lr=&source=gbs_navlinks_s.

Kolb, D. A., Boyatzis, R.E., & Mainemelis, C. (2000). Experiential learning theory: Previous research and new directions. In Sternberg, R. J., & Zhang, L. (Eds.), *Perspectives on thinking, learning, and cognitive styles* (227-247). Mahwah, N.J: Lawrence Erlbaum Associates.

Linden, K.V. (2006). A grounded approach to the study of complex systems. *World Futures, 62*(7), 491-497. doi:10.1080/02604020600912806

Marshall, S. P. (2006). *The power to transform: Leadership that brings learning and schooling to life*. San Francisco, CA: Jossey-Bass.

Meadows, D. (1999). Leverage points: Places to intervene in a system. Hartland, VT: The Sustainability Institute.

Meadows, D. H., & Wright, D. (2008). *Thinking in systems: A primer*. White River Junction, VT: Chelsea Green Publishing.

Metz, S. (2012). Systems thinking. *The Science Teacher*, *79*(7), 6. Retrieved from http://go.galegroup.com/ps/i.do?id=GALE%7CA307184829&v=2.1&u=vol_b92b&it=r&p=ITOF&sw=w

Mitchell, M. (2009). *Complexity: A guided tour*. New York, NY: Oxford University Press.

Montuori, A. (2015). Complexity and transdisciplinarity: Reflections on theory and practice. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 170-200). New York, NY: Routledge.

NGSS Lead States. (2013). *Next Generation Science Standards*: For states, by states; Appendix A: Conceptual shifts in the *Next Generation Science Standards*. In *A Framework for K-12 Science Education: Practices, crosscutting concepts, and core ideas*. Washington, DC: Achieve, Inc. Retrieved from http://www.nap.edu/catalog.php?record_id=13165

Patton, M. Q. (2002). *Qualitative research and evaluation methods*. Thousand Oaks, Calif: Sage Publications.

Plate, R., & Monroe, M. (2014). A structure for assessing systems thinking. *The Creative Learning Exchange*, *23*(1), 1-6. Retrieved from http://www.clexchange.org/ftp/newsletter/CLEx23.1.pdf

Richmond, B. (1993). Systems thinking: critical thinking skills for the 1990s and beyond. *System Dynamics Review*, *9*(2), 113-133. doi:10.1002/sdr.4260090203

Senge, P. M. (2000). *Schools that learn: A fifth discipline fieldbook for educators, parents, and everyone who cares about education*. New York: Doubleday.

Senge, P. M. (2012). Creating schools for the future, not the past for all students. *Leader to Leader*, (65), 44–49. doi:10.1002/ltl.20035

Shenton, A. K. (2004). "Strategies for ensuring trustworthiness in qualitative research projects." *Education for Information*, *22.* 63-75. Retrieved from http://search.ebscohost.com.ezproxy.uvm.edu/login.aspx?direct=true&db=aph&AN=13857302&site=ehost-live

Sung, N. S., Gordon, J. I., Rose, G. D., Getzoff, E. D., Kron, S. J., Mumford, D., … Kopell, N. J. (2003). Educating future scientists. *Science*, *301*(5639), 1485. doi:10.2307/3835062

Sweeney, L. B. (n.d.). Thinking about systems: 12 habits of mind. Linda Booth Sweeney. Retrieved from http://www.lindaboothsweeney.net/thinking/habits.

Sweeney, L. B. (2009). Systems teaching and farm-based education. Reprinted in Farm Based Education Network. (n.d.). Retrieved February 19, 2015, from http://www.farmbasededucation.org/page/systems-teaching-and-farmbased

Sweeney, L. B. (2014). Learning to connect the dots: Developing children's systems literacy. CLEx23.2.pdf. Spring 2014. 1-12.

Sweeney, L. B., & Meadows, D. (2010). *The systems thinking playbook: Exercises to stretch and build learning and systems thinking capabilities*. White River Junction, VT: Chelsea Green Pub.

Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, *16*(4), 249–286. doi:10.1002/sdr.198

Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review*, *23*(2-3), 285–311. doi:10.1002/sdr.366

Toscano, P.M. (2006). The study of global solutions: A postmodern systems thinking view of grounded theory/grounded action. *World Futures: The Journal of New Paradigm Research, 62*(7), 505-515. doi:10.1080/02604020600912848

Wagner, T. (2008). *The global achievement gap: Why even our best schools don't teach the new survival skills our children need--and what we can do about it*. New York, NY: Basic Books.

Waters Foundation. (2014). Habits of a systems thinker. Systems Thinking in Schools. Retrieved from http://watersfoundation.org/systems-thinking/habits-of-a-systems-thinker/

Weil, Zoe. (2012, July 2). Solutionaries: Zoe Weil at TEDxConejo. Retrieved from http://humaneeducation.org/blog/2012/07/02/solutionaries-zoe-weils-new-tedx-talk/

Wessels, T. (2006). *The myth of progress: Toward a sustainable future.* Burlington, VT: University of Vermont Press.

Becoming Systems Literate

Complex systems (e.g., ecological, biological, political, and social systems) are ubiquitous and overlapping. For this reason, the theme of complexity resonates across disciplines and domains. Over the past half century, a complexity frame of reference (Byrne & Callaghan, 2014) has become increasingly central to advancing knowledge and improving practice across a range of fields from the hard sciences to public policy. The author argues that developing systems literacy in the population at large will be central to informing collective decision making around interrelated issues like climate change and inequality in the changing years ahead. This article presents one slice of a grounded theory study analyzing texts by and interviews with systems scholars and educators. It summarizes a definition of systems literacy detailed in an earlier article before presenting five new findings to posit that one becomes systems literate through an iterative, nonlinear process of grounding, questioning, broadening, integrating, and developing a systems lens. The article closes by discussing implications for K-16 education and possibilities for further research.

Keywords: Systems literacy, complexity, grounded theory, education

Introduction

In 2014 at the Relating Systems Thinking and Design Symposium in Oslo, Norway, Hugh Dubberly of Dubberly Design Office delivered a keynote address titled "A Systems Literacy Manifesto." In it, he argued,

> No matter what we call them, most of the challenges that really matter involve systems, for example, energy and global warming; water, food, and population; and health and social justice. And in the day-to-day world of business, new products that create high value almost all involve systems, too. (p. 2)

Though Dubberly's primary focus was on design and design education, in his talk, he also made a more general case for educating systems literate citizens in the population at large.

Dubberly is not alone in promoting systems education. Many authors have argued that in order to prepare students to face complex problems at the intersections of social, economic, and ecological domains, we must teach them the skills of analysis and synthesis associated with systems thinking (e.g., Betts, 1992; Fisher, 2011; Forrester, 2009; Plate, 2006; Senge, 2012; Sweeney, 2014; Wessels, 2006). Organizations like the Waters Foundation and the Creative Learning Exchange have developed and promoted approaches to systems education for decades (see Fisher, 2011), and systems thinking has long been a core concept in the field of education for sustainability (Cloud, 2012; Shelburne Farms' Sustainable Schools Project, 2011; Sweeney, 2009). Within the past few years, systems have emerged as a theme in mainstream education, too, most prominently as cross-cutting concepts and core ideas in the *Next Generation Science Standards* and the new *C3 Framework for Social Studies State Standards* (National Council for the Social Studies, 2013; NGSS Lead States, 2013). Complex systems—biological, ecological, economic, social, political, etc.—are ubiquitous. The idea of teaching students to study, track, model, and engage with them is gaining traction, but there remains much work to be done on this front.

Sweeney (2009) argued that without systems literacy, "we continue to operate from crisis to crisis, stuck on the problem solving treadmill, where our 'solutions' often only create more problems or make the original problem worse" (n.p.). Dubberly (2014) offered examples like climate change denial and blind faith in failed economic models to illustrate the implications of systems illiteracy among decision makers and the population. This illiteracy, he said, "is a symptom that *something is missing* in public discourse and in our schools" (p. 2). He argued, "We must build systems literacy. To not do so would be irresponsible" (p. 10). This article, one slice of a larger study, seeks to contribute to the conversation about *how* to build such literacy.

Systems Literacy

A *system* is a series of parts that together constitute a single whole. Systems can be *simple* (e.g., a row of dominos set to tip over or a toaster), *complicated* (e.g., a jet or a Rube-Goldberg-style machine), or *complex* (e.g., an animal, an ecosystem, a community). These concepts have been defined and the distinctions have been delineated in detail in myriad contexts (see, e.g., Ackoff, 1997; Geert & Steenbeek, 2014; Grauwin, et al., 2012; Manson, 2001; Mitchell, 2009; Wessels, 2006). The concept of *systems literacy*, though, is less well developed in the literature. Within the world of K-12 education, several authors and organizations have generated resources and documents outlining the knowledge, skills, and dispositions relevant to a systems thinking and system dynamics education (see e.g., Plate & Monroe, 2014; Richmond, 1993; Sweeney & Meadows, 2010; Waters Foundation, 2014). A few have worked explicitly with the term *systems literacy* too (Plate & Monroe, 2014; Sweeney, 2014). But solidifying a definition of *systems literacy* was an essential first step to tackling the question *How does one become systems literate*?

In his keynote address, Dubberly (2014) argued that systems literacy must encompass a systems vocabulary along with skills for "reading" and "writing systems" and that it must be rooted in the literature and history of systems. Furthermore, it must illuminate connections between different types of systems and between disparate disciplines and domains. Sweeney, a leader in the field of systems thinking education, defined systems literacy briefly as "an applied understanding of living systems" (in Bennett & Sweeney, n.d., n.p.). "To be literate," Sweeney (2014) explained, "means to have a well-educated understanding of a particular subject, like a foreign language or mathematics." She went on to say, "The knowledge must be both comprehensive and abundant enough that you are capable of putting it to use. Systems literacy represents that level of knowledge about complex interrelationships." (p. 4).

Previous definitions of systems literacy were developed largely at the intersections of systems thinking, systems dynamics, and K-12 education. Through a grounded theory exploration of complex systems and education, this study built forward on that work in three ways: (1) by using the *Literacy in 3D* conceptual model to unpack systems literacy in terms of its cultural, operational, and critical dimensions (Green & Beavis, 2012); (2) by identifying common themes and patterns across a series of text-based sources delineating skills and knowledge associated with systems thinking and systems education; and (3) by interviewing scholars and educators who explore complexity across a wide range of disciplines and domains. In this way, this study has drawn on voices and texts from many branches of complexity (including chaos and complexity theory in math, complexity theories in the social sciences, and transdisciplinary complex systems research methods, among others) to develop a deeper understanding of what it means to be systems literate. The working definition is summarized below and described in greater detail in a previous article (Author, under review).

Systems Literacy Across Three Dimensions

In Green's *Literacy in 3D* model, the cultural dimension involves the terms and conventions used to make meaning within a particular subject. The operational dimension involves skills and practices associated with communicating across a range of contexts within a subject-specific culture. The critical dimension emphasizes the socially constructed and selected nature of established knowledge and practices and requires explicit recognition of the selection criteria at play. It focuses, essentially, on *what counts* as knowledge within a subject and *why*. Thus a person who is culturally, operationally, and critically literate within a particular subject has access to the meaning system or culture of that subject and not only the potential to function effectively and productively within that culture, but also the ability to produce and transform the culture of that domain (Green & Beavis, 2012).

This conceptual framework added structure and depth to an exploration of the concept of systems literacy. The resulting definition is the product of careful analysis of five existing texts delineating knowledge, skills, and dispositions associated with systems education (Dubberly, 2014; Plate & Monroe, 2014; Richmond, 1993; Sweeney, n.d.; Waters Foundation, 2014) and data from interviews with 22 complexity scholars and educators working in a wide range of fields including anthropology, political science, electrical and environmental engineering, math and statistics, public administration, political science, food systems, and sustainability education, among many others.

The following sections summarize the definition of systems literacy then describe research methods used to build forward from that definition to a grounded theory of how one becomes systems literate. Five findings described below outline an iterative, nonlinear process of becoming captured loosely by the terms *grounding*, *questioning*, *broadening*, *integrating*, and *developing a systems lens*. The article closes with a discussion of some implications of these findings for the world of K-16 education.

Systems Literacy Defined

The ten components organized under three dimensions of systems literacy below represent a synthesis of concepts that emerged across 22 transcribed interviews and five text-based data sources (Dubberly, 2014; Plate & Monroe, 2014; Richmond, 1993; Sweeney, n.d.; Waters Foundation, 2014).

The Cultural Dimension

Within the cultural dimension, systems literate individuals see the world holistically, recognizing systems (biological, ecological, political, economic, social, etc.) as nested, interdependent parts of a greater whole. They know the language of complex systems (and may be familiar with the history and core texts of systems thinking, complex systems sciences, and/or another branch of complexity studies), and they employ that language and systems thinking (intuitively and/or systematically) to 'read' the world around them (Dubberly, 2014). They are adept at seeing connections between parts and wholes; between seemingly disparate subjects, fields, and ideas; and between patterns across diverse contexts. Their holistic interpretations of the world around them are rooted in understandings about the self-organizing nature and emergent properties of complex systems.

Table 1
Three components of the cultural dimension of systems literacy

Systems literate individuals . . .
(1.1) know the context and language of complex systems stemming from at least one branch of complexity studies (e.g., complexity theories, systems thinking/system dynamics, complex systems computational methods, etc.)
(1.2) read the world through a systems lens, actively employing systems thinking and/or a complexity frame of reference to see connections between parts and wholes, between diverse subjects and ideas, and between common patterns across contexts
(1.3) comprehend self-organization and emergence, understanding how nestedness, interdependence, and scale impact adaptation, evolution, and emergent properties

(Author, under review)

The Operational Dimension

Within the operational dimension, systems literate individuals use systems knowledge, skills, and understandings to inform and advance their work in a range of contexts. This may involve developing systems-compatible research methods, systems-informed mathematical models, or systems-sensitive policies and designs. The reverse is true as well. Systems literate individuals employ domain-specific knowledge (e.g., natural laws, established theories, effective strategies) and skills (e.g., data analysis, computer modeling, design) to increase their understanding of complex systems. They strive to understand and communicate how the world really works rather than how it works in theory (see, e.g., Richmond, 1993). They do this by embracing ambiguity (see, e.g., Marshall, 2006; Montuori, 2015), allowing room for complicated truths and shades of gray, recognizing not only the structure of a system that contains and limits possibilities but also the agency of individuals to assert themselves within and even alter those structures. They remain open to new and contradictory information, because such information can help them to understand more fully. They avoid over-simplified explanations of cause-and-effect when tracking patterns of change over time. They employ scientific inquiry and empirical methods to test assumptions, fine-tune situational understandings, and reject hypotheses that do not stand up to scrutiny. Finally, they employ multiple modes of communication (from computer modeling and graphic design to analytical writing and creative storytelling) to develop their own understanding of the systems around them and to communicate those understandings in meaningful, impactful ways.

Table 2

Four Components of the Operational Dimension of Systems Literacy

Systems literate individuals . . .
(2.1) cross disciplinary boundaries, using knowledge about systems to enhance domain specific knowledge and skills (e.g., knowledge and skills in math, computing, data analysis, design, policy work, etc.), and vice versa
(2.2) employ scientific inquiry and empirical methods to understand reality, emphasizing both structure and agency, remaining open to new and contradictory information, and embracing ambiguity and uncertainty
(2.3) work to understand nonlinear change, looking beyond simple cause-effect relationships to identify underlying variables and patterns of change over time, anticipate unintended consequences, identify points of leverage, and design effective solutions
(2.4) activate multiple modes of communication (which may include the creation of computer simulations, graphic illustrations, written descriptions, etc.) throughout the learning process to structure thinking and construct and share knowledge and understanding

(Author, under review)

The Critical Dimension

The three dimensions of the *Literacy in 3D* model are interdependent. They act simultaneously (Green & Beavis, 2012). Thus, there is a great deal of overlap between the dimensions of systems literacy. In particular, many components of the cultural and operational dimensions are also inherently critical. Three components, though, are not so much about language in the cultural/meaning or the operational/communication form. Rather they emphasize language and meaning as sources of power. Therefore, these components fall predominantly within the critical dimension.

Within the critical dimension, systems literate individuals pursue multiple perspectives, understanding that each individual's particular point of view represents one part of the truth, one slice of the whole. They recognize the power of mental models—"assumptions about how the world works" (Sweeney, n.d., n.p.)—to affect how they see and understand their world, and they uncover and test such assumptions to improve their ability to make sense of and describe reality (see, e.g., Sweeney, n.d.; Waters Foundation, 2014). Systems literate individuals follow the thread of a complex system across disciplines and contexts (Meadows & Wright, 2008). As new information leads to new questions, they engage in active, adaptive learning. In this way, literacy is not only a thing to be developed, but also a tool through which knowledge, skills, and understandings build upon and reinforce one another (Green & Beavis, 2012).

Table 3
Three Components of the Critical Dimension of Systems Literacy

Systems literate individuals . . .
(3.1) pursue multiple perspectives in a given situation to avoid polarized or dichotomous thinking and increase personal and collective understanding
(3.2) recognize the power of mental models and challenge assumptions and heuristics that limit one's ability to align understanding with empirical evidence
(3.3) engage in active, adaptive learning to develop skills required for new situations and to make meaning out of new information

(Author, under review)

These ten components organized within three dimensions constitute a basic definition of systems literacy. For more details and examples supporting this definition, see "Systems Literacy in Three Dimensions: Cultural, Operational, and Critical Competencies for Living in a Complex World" (Author, under review). The following sections describe the final phase of this research study, which built forward from this working definition to develop a grounded theory of how one becomes systems literate.

Research Design

The extended study employed grounded theory methods informed by a complexity frame of reference (Byrne & Callaghan, 2014; see also Stillman, 2006; Toscano, 2006). A qualitative approach to inquiry with a long tradition in the social sciences, grounded theory is designed for open-ended exploration and discovery (Corbin & Strauss, 2008; Creswell, 2013; Patton, 2002). Because grounded methods build toward rich descriptions of concepts and theories of process (Corbin & Strauss, 2008), they provided a useful structure for exploring the core research questions: *What is systems literacy?* and *How does one become systems literate?*

Grounded theory methods consist of systematic guidelines for drawing patterns out of raw data (Denzin & Lincoln, 2000). In this context, theory is not produced through logical deduction based on "a priori assumptions" (Patton, 2002, p. 125). Instead, it is built out of the observations of a researcher interacting with participants in the real world (Creswell, 2013; Denzin & Lincoln, 2000; Patton, 2002). Importantly, grounded theories are not fixed artifacts. Rather, they are explanations of data open to testing, refinement, and revision through further research (Linden, 2006; Stillman, 2006).

Data collection methods are relatively open-ended (Charmaz, 2000). They typically involve semi-structured interviews, though other strategies (e.g. surveys, document analysis, etc.) are acceptable (Patton, 2002). Analysis involves unpacking data in terms of categories, properties, and dimensions; and reconstructing that data to illuminate patterns and processes, often through narrative explanations. Rather than aiming for findings representative of populations, grounded theorists are concerned with *concepts*—ideas contained in data (Corbin & Strauss, 2008). These concepts not only emerge out of the data; they also drive further collection through *theoretical sampling* (Charmaz, 2000; Corbin & Strauss, 2008). Concepts are unpacked through *comparative analysis,* a process of systematically comparing and contrasting incidents in search of patterns and common characteristics as well as variation and negative cases (Corbin & Strauss, 2008; Linden, 2006). Comparative analysis informs theoretical sampling in a cyclical fashion as new data points toward either saturation or conceptual gaps (Creswell, 2013).

Research informed by a complexity frame of reference must address a series of challenges, among them the challenge of balancing analytic reductionism with more holistic approaches to knowledge (Umphrey, 2002) and the challenge of developing new knowledge in the context of continuous change (Patton, 2002). Grounded theory is well equipped to address these challenges (Byrne & Callaghan, 2014; Corbin & Strauss, 2008; Patton, 2002). It is both reductive/analytic and synthetic/constructive by design. Grounded theory methods are excellent for generating ideas, grounding knowledge in context and experience, and opening conversations rather than closing them. In this way, grounded theory methodology meets the second challenge of complexity informed research, generating practical knowledge in a changing world (Byrne & Callaghan, 2014). The theory presented in this article, a theory of how one becomes systems literate, is by design a work in progress.

Data Sources and Methods

Study participants included 22 academics and educators across a wide range of fields of study, all of whom incorporate complex systems concepts and methods in their research and/or instruction. The sample, presented in Table 4 below, included six women and sixteen men from twelve different educational institutions.

This study was launched off of an assumption that among scholars, authors, and educators researching, writing about, and teaching about systems thinking and complexity-informed methods and concepts, one would find examples of systems literacy at its highest levels. Through interviews, participants were asked not only what they need to know, understand, and be able to do in their work as it relates to complex systems, but also how they developed such knowledge, skills, and dispositions through their formal and informal educational paths.

While this research was underway, the book *Journeys in Complexity: Autobiographical Accounts by Leading Systems and Complexity Thinkers* was published. Edited by Montuori (2015), the book is a compilation of essays, in which authors identified and described key experiences in their lives leading to their current understandings of and work within the field of complexity studies. Because this text was highly relevant to this study, several of the essays along with three more from the original review of literature for the extended study were included as data sources for analysis (Burneko, 2015; Byrne, 2014; Combs, 2015; Eisler, 2015; Forrester, 2007; Goerner, 2015; Low, 2015; Montuori, 2015; Ogilvy, 2015; Olds, 2015; Sahtouris, 2015; Sterman, 2002).

Twenty-two transcribed interviews and twelve complexity scholars' personal essays resulted in a full sample of 34 cases in all. Across these cases, five common themes emerged to constitute a grounded theory of how one becomes systems literate.

Table 4
Participants

Pseudonym	Profession	Department/Domain
Alex	Professor	Mathematics and Statistics
Ben	Middle/high school teacher	Science
Beth	Professional developer	K-12 Education
Bob	Professor	Classics
Charlotte	Professor	Computer Science
Daniel	Professor	Public Administration and Policy
Dawn	Professor	School of Engineering
Elizabeth	Educator	K-12 and Teacher Education
Emmett	Professor	Communication Management and Design
Ethan	Professor	Anthropology and Archaeology
Gavin	High school teacher	Social Studies
Genevieve	Professional developer	K-12 Education
Henry	Professor	Public Administration and Policy
Jake	Professor	Environmental Studies and Sciences
Madeline	Professor	Biochemical Engineering
Matt	Professor	Electrical Engineering
Max	High school teacher	Science and Food Systems
Nick	Professor	Comm. Development and Applied Economics
Noah	Professor	Political Science
Oliver	Professor	Information Technology
Simon	Professor and dean	Environmental Humanities
William	Professor	Mathematics and Statistics

(Author, under review)

Credibility of Findings

To establish the credibility of a study, Shenton (2004) advocated for identifying the background, biases, and qualifications of the researcher. This recommendation is relevant to this study. Developing my own systems fluency has been a goal of my professional and academic career since I was introduced to the concept of complex systems and its potential for connecting student learning across disciplines several years ago. Because of my own connection to the subject of my study, I needed to be thoughtful and thorough in validating my interpretations.

To increase the dependability of my findings, I have sought a variety of perspectives and conducted several rounds of member checking to critique and refine my interpretations along the way and to ensure that my findings are grounded data rather than my own "characteristics and preferences" (p. 72). In particular, I shared drafts of the definition of systems literacy outlined above and the five findings presented below with ten and seven participants, respectively. Their feedback informed revisions. Finally, through all phases of this study I have welcomed "opportunities for scrutiny of the project by colleagues, peers and academics" (p. 67).

Becoming Systems Literate

As would be expected, the formal and informal educational paths of 22 participants (as described in interviews) and twelve authors (as described in published essays) were not identical. Though each individual had come to incorporate some version of complex systems concepts and methods in his or her work, each arrived at that place in a unique way. And yet, across these 34 cases, themes and patterns did emerge. Those themes are presented at a glance in Figure 1 below and described in greater detail in the sections that follow.

Grounding	Questioning	Broadening	Integrating	Developing a systems lens
In natural and manmade systems, incl. communities and social systems, esp. agricultural or food systems In real-world problems In one or more disciplines	Asking big questions (and exploring 'and/also' rather than 'either/or' answers) Questioning methodologies, ontologies, mental models, and personal biases Questioning established structures to explore better solutions Embracing ambiguity and uncertainty	Broadening through formal education Broadening through independent or collaborative learning and non-academic experiences	Integrating knowledge across fields and experiences Integrating academic and intuitive knowledge (through tension) Integrating through narrative Learning, integrating, adapting, evolving	Learning the culture (i.e., language, literature, history) of complexity Developing a systems lens through formal and informal education Refining a systems lens through modeling and experimentation
Experiencing, experimenting, engaging, acting.				

Figure 1. **Common themes in becoming systems literate.**

Grounding

G1. Grounding in Natural and Manmade Systems

Because living systems are complex systems, it is not surprising that some participants pointed to a connection with the natural world and early experiences exploring natural spaces when discussing the process of becoming systems literate. Knowledge of and familiarity with natural systems can help one to make sense (through metaphor and example) of more abstract social systems that can be harder to see. More striking though, was the number of participants who spoke of experiences on farms or with other agricultural or food systems. In terms of developing systems literacy, there seems to be real power in grounding oneself in contexts that exist at the intersections of natural and manmade systems (see Sweeney, 2009). Forrester (2007), author of "System Dynamics—A Personal View of the First Fifty Years," wrote of his childhood on a ranch in Nebraska, "A ranch is a crossroads of economic forces. Supply and demand, changing prices and costs, and economic pressures of agriculture become a very personal, powerful, and dominating part of life" (p. 345).

Bob, an academic and active farmer explained, "Anybody who's working in a kind of subsistence mode—and people who farm are in a way . . . you're trying to make it work . . . to make do with . . . and make the most of what you have." He went on, "There's something inherently complex-systems-like and sustainability-like in that kind of situation." Genevieve, who works in K-12 professional development, described how working on a horse farm as a teenager helped her to develop a greater awareness of patterns related to weather and food. She described being especially struck by the death of a single horse and the way that loss reverberated through the herd. "This was an old horse," she said, "and I had no sense that he was the herd leader. I didn't have that awareness." She identified this event as the beginning of a new understanding: "I had this real sense of, like, pluck this thing out and it changes everything. It was just so visible for me. . . . And part of what was cool was I also understood that I could influence it." Real experiences with complex systems can be surprising, disorienting, and, as Genevieve described, empowering.

Beth, also a K-12 professional developer, spoke of developing a foundation for systems thinking while working for her parents as a child. She said, "Interacting with people from all different walks of life in a retail, service-oriented kind of business . . . was a really great experience . . . to see how different aspects of that system work, how I could tweak things." The pragmatism, resourcefulness, and creativity that are central to systems literacy seem often to have roots in tangible, concrete experiences in real systems. And yet, for the sheer number of times that agricultural systems arose in interviews and appear the literature, it seems clear that experiencing life tied to real consequences at the intersection of human and natural systems is a powerful force for grounding oneself in complexity. As Bob explained, a farmer he does not have to be consciously aware of complexity. It is embodied in his work. (The processes described above support the development of systems literacy components 1.2, 2.2, 2.3, 3.2, and 3.3. See Table 6 on page 100.)

G2. Grounding in Real World Problems

What was most interesting about interviews with participants was not that these individuals were studying complexity in and of itself but that they were using their transferable understandings of complex systems along with complexity-informed research and simulation methods to explore concrete, highly relevant, real world problems. They discussed collaborating across disciplines and beyond the world of academia to research problems like cascading failure in electrical grids, ground water remediation, and antibiotic resistance. Grappling effectively with real world problems means acknowledging and addressing real world complicating factors. An environmental engineer, Dawn spoke of working on problems at the intersections of environmental concerns, human policy, and economics. Similarly, Oliver, a professor of information technology, discussed using scenario planning to support organizations through change initiatives across a wide range of contexts. He explained how "the interactions of multiple stake-holders and the legitimacy of multiple and conflicting opinions make decision analysis [and] decision making very challenging." Systems theorists have identified complex problems by a range of names including system messes (Ackoff, 1997), wicked problems (Conklin, 2009), and 21st century problems (Rogers, Pfaff, Hamilton, & Erkan, 2013). Like those theorists, participants in this study acknowledged that real world problems are connected and solutions are interdependent. (Systems literacy components: 1.2, 2.1, 2.2, 2.4, 3.1, 3.3)

G3. Grounding in One or More Disciplines

Participants described being grounded in real world systems and grounding their work in solving real problems, but each was also grounded in one or more academic traditions. When asked about the knowledge and skills required for grappling with complex systems, several participants emphasized the value of a strong background in science, math, statistics, and/or computational thinking. Byrne (2014), author of "Thoughts on a Pedagogy OF Complexity," explained, "Even more important than conventional competence in the use of mathematical and statistical methods is an understanding of what Mathematics is" (p. 44). He emphasized that reality is messy and explained, "From that perspective mathematics is not a way in which we grasp the transcendental ideal but rather a very useful source of metaphors which are linked to each other through chains of formal proof" (p. 45). William, a professor of math and statistics, advocated for educating "hybrids." He said students need "a really strong background in math and computing and stats as they emerge from undergrad or from high school, but they need to be layering . . . other stuff on as well."

Though complexity does have strong ties to math, science, and computers, it is truly a transdisciplinary lens. Applying the systems lens effectively across fields requires some level of domain expertise. Ethan, a professor of archeology and anthropology, illustrated the value of deep grounding in a particular field through concrete examples: We don't expect just anybody to be able to build a house, do your plumbing, or fix a car, he explained. We accept that it takes training and experience to prepare people to do that work. People are trained to do things, he said, "and they're better at those things, because they know how to do them. They have knowledge of them." Developing a depth of knowledge in one or more fields supports the development of systems literacy that transfers across fields. (Systems literacy components: 2.1, 2.2)

Questioning

Q1. Asking Big Questions

Charlotte, a professor of computer science, named a solid grounding in science and hard computational skills as central to grappling with complexity, "but the main things," she said, "are just curiosity and a willingness to keep asking questions and working and teaching yourself." Many participants spoke of asking questions, big questions without simple answers (e.g., "How do you make energy more sustainable?" and "How did life begin?"). Ethan talked about posing big questions to undergrads in his anthropology classes: "Hell, there's some of these questions that I haven't answered or people that are way smarter than I am in anthropology haven't answered." He went on, "I think that's a good thing for people to know at a young age that we don't have it all figured out."

Several participants explained that they were not particularly interested in yes-or-no questions, or right-or-wrong answers. In "System Patterns and Possibilities," Olds (2015) wrote, "The fundamental intuition throughout my life has been that truth, however we define it, lies 'in the between'" (p. 17). Some participants spoke about working on open-ended questions in real world contexts in contrast to testing hypotheses in isolation. Some spoke of answers evolving as they expanded the boundaries of their exploration, pulled more pieces of a puzzle together, considered the same question in a different context or at a different scale, or imagined different answers being optimal under different constraints. Matt described drawing on diverse perspectives in connecting his research in electrical engineering to issues of public policy. Complex systems, he said, is about "noticing that when you put the pieces together, you get a different answer than if you just looked at the pieces individually."

Some participants described tackling questions about the future. Ben, a middle school science teacher, explained, in the field of system dynamics, "Time is on the x-axis always. It's always making predictions about what the system is going to do." Daniel, also a system dynamics scholar and professor of public administration, asked, "I may have to do some things right now that'll take 35 years or a generation to make a difference. So how do I know what's right?" He talked about exploring multiple possibilities through simulation models. Oliver talked about testing predictions through playing out scenarios. In the context of a new initiative not performing as predicted, his question became: "It didn't work. Why?" 'Why' questions were common. In his essay "All Models Are Wrong: Reflections on Becoming a Systems Scientist," Sterman (2002) explained, "It's by asking those 'why' questions that we gain insight into how we are both shaped by and shape the world, where we can act most effectively, where we can make a difference—and what we are striving for" (p. 527). (Systems literacy components: 1.2, 2.2, 2.3, 3.1, 3.2, 3.3)

Q2. Questioning Methodologies, Ontologies, Mental Models, and Personal Biases

Several participants talked about the limitations of traditional research methods. Ben spoke of discovering through his graduate research on the genetics of a particular species of beetle, "There are things that statistics will tell you about the way that things should work, but the real world is an incredibly connected piece of work." Noah, a professor of political science, spoke of the "false assumptions" embodied in much statistical analysis. Rather than rejecting statistics as a flawed explanatory device, he talked about using mixed methods, a blend of quantitative and qualitative approaches to answer different slices of a question. Emmett, a professor of communication management and design, talked about the potential for disciplinary training to restrict one's vision. He described challenging undergraduates in an interdisciplinary course to wrestle with questions like "What is your major? What are the objects of study? What are the assumptions that are made? What are the methods, and how are those completely different than the person sitting next to you?"

Several authors and organizations have identified the practice of questioning mental models and surfacing underlying assumptions as central to systems thinking (e.g., Sweeney, n.d.; Waters Foundation, 2014). Sterman (2002) wrote, "It's one thing to point out that someone *else's* opinions are 'just a model'—it's quite something else to recognize the limitations of our *own* beliefs" (p. 526). He advocated for "the rigorous and disciplined use of scientific inquiry [to] uncover our hidden assumptions and biases" (p. 501). Ethan talked about the practice in the field of anthropology of "constantly questioning how we know what we know." He said,

> But that's what science is supposed to be. That questioning is supposed to be at all levels. It's not just supposed to be about individual, you know kind of research problem hypothesis level. It's supposed to be all the way up to what's this big overarching theory that I'm working under. Does this challenge that?

(Systems literacy components 2.2, 3.1, 3.2)

Q3. Questioning Identities and Social Structures

How does one come to question one's own worldview? Some participants pointed to experiences growing up in multicultural communities or moving from one country and culture to another. Some described eye-opening experiences through travel. Others spoke of close family members practicing different religions. Elizabeth, and educator in the domains of K-12 and teacher education, talked about how early and lasting exposure to a range of cultures, ethnicities, and religions allowed her to feel flexible in her own identity. Her description of early experiences with religion are just one example: "I grew up in a household where my grandfather was Catholic, became a Buddhist. My dad went to the Hindu temple sometimes and the Buddhist temple sometimes. My mother took me to church." In "Complexity and Transdisciplinarity: Reflections on Theory and Practice," Montuori (2015) described his own multi-cultural, multi-national life, saying,

> My experiences made me very aware of the nature and power of categories and perspectives, of different ways of seeing the world. They instilled a fascination with epistemology at a young age. More specifically, they made me aware that human beings see the world in many different ways. (p. 172-173)

The ability to question one's worldview translates fairly naturally into questioning established social norms and structures. More than one participant discussed the need to think critically about alternatives to today's cultural and economic status quo. This theme resonated in the literature in interesting ways. As Ogilvy (2015) wrote in "Systems Theory, Arrogant and Humble," "The fact that values are not universal is a feature, not a bug" (p. 15). (Systems literacy components: 3.1, 3.2, 3.3)

Q4. Embracing Uncertainty and Ambiguity

Asking big, open-ended questions, seeking multiple perspectives and empirical evidence in answering them, and grappling with questions that truly can't (in the short term at least) be fully answered seems to instill in people a series of dispositions. Participants spoke about being comfortable with conflict, opposition, ambiguity, and uncertainty, and being sensitized to variation and change. The themes of embracing uncertainty and ambiguity are common in the systems literature (see, e.g., Low, 2015; Marshall, 2006; Morgan, 2006; Montuori, 2015; Olds, 2015; Patton, 2011). Along these lines, Elizabeth spoke of having a high tolerance for dissonance: "You know, if you have five perspectives, it is cognitively a little disturbing." She talked about what she called cognitive agility, "the ability to say it can be A or B. It doesn't have to be yes or no. It could be five things." She said, "I can skip in this agile way, my mind from option one, two, three, four, five. So that agility is really powerful. But if then you're very agile and you're open to these multiple perspectives, then you're never finished." A good question can change a person's trajectory. For some participants, big, open-ended questions inspired them to dig in and learn, leading to the next process in becoming systems literate: broadening. (Systems literacy components: 2.2, 3.1, 3.3)

Broadening

B1. Broadening Through Formal Education

"My educational path is completely circuitous and bizarre," said Jake, describing an academic career that resulted in a bachelor's, master's, and two doctoral degrees in four branches of science ranging from ecology to quantum mechanics. Though Jake's particular path was certainly unique, almost every participant described a broad academic background. Charlotte said, "I just had courses all over the place: physical science, social science, math, mostly biological and physical sciences. It gave me the underlying intuition and knowledge about the world to be able to apply these things in more meaningful ways." A few participants spoke of a broad liberal arts background that allowed them to dabble in many fields. Gavin, a high school social studies teacher, emphasized how the diversity of his liberal arts studies developed his ability "to think in a lot of different ways."

Several participants spoke of switching majors multiple times. Some described enrolling in courses well beyond the scope of their major, because they were interested in other things. Others talked about pursuing a particular field (like classics, anthropology, and linguistics) that required them to develop a depth of knowledge in a wide range of fields. Bob explained how being a classicist forced him to be well versed in history, archeology, demographics, sociology, prose and poetry, not to mention multiple languages. One notable exception to the pattern of broadening was Simon. His educational path was very straightforward, earning him a B.A., M.A., and Ph.D. in English. But, he said, his dissertation focusing on 19th century environmental literature was largely rooted in cultural and environmental studies, and he described having to defend to his advisor how his work fit within the confines of an English program. (Systems literacy components: 2.1, 3.1, 3.3)

B2. Broadening Beyond Formal Education

In describing their educational paths to complexity, many participants spoke of learning experiences beyond the walls and halls of schools and universities. Elizabeth, tracked into a science focus in high school said, “I enjoyed the kind of scientific thinking, but at home it was all books and stories and literature.” She described how literature and philosophy, read both for school and for fun, informed her evolving thinking. Participants spoke of continually expanding their own knowledge through reading, attending lectures, and exploring new bodies of knowledge on their own or collaboratively with colleagues. Several talked about learning new content, skills, software, or algorithms to tackle particular problems. Jake described starting a new environmental studies program at his university. “I needed to become a hyper generalist like instantly,” he explained. He, like many others, talked about teaching himself what he needed to know and seeking out people with domain expertise they were willing to share. Finally, participants described how their extracurricular interests (in performing and composing music, reading and writing literature, exploring or practicing religion/spirituality, building, farming, etc.) intersected with their academic interests. Bob said, “The more versatile one is in one’s experience . . . the more likely you’re going to be a systems thinker, I think. Or predisposed to be one.”

The concept of broadening is supported in the literature. Several authors (e.g., Byrne, 2014; Goerner, 2015; Montuori, 2015; Olds, 2015) have written about it. Describing his own broad background in physiology, biology, chemistry, calculus, statistics, social policy, economics, and political philosophy, Byrne (2014) said,

> It is precisely this broadening which seems essential to me as a basis for allowing students to engage sensibly with the implications of the complexity frame of reference for understanding the social world and the intersections of that social world with the natural world within which it is embedded. (p. 44)

(Systems literacy components: 1.2, 2.4, 3.1, 3.3)

Integrating

I1. Integrating Knowledge Across Fields and Experiences

Broadening provides participants with a diverse range of knowledge. Integrating draws that knowledge together through a process of identifying patterns and connections. Jake explained, “By switching expertise several times . . . one possibility is that you would just be an expert in [multiple] things, but rather than that, I’ve started blending these things together.” Similarly, Olds (2015) wrote:

> For me the search for understanding has always required the language of ‘and/also’ rather than ‘either/or.’ This has made me an integrator in most contexts and given me a powerful desire to foster communication between conflicting forces or perspectives, arriving at a larger creative harmony. (p. 18)

This theme of integrating resonated through texts and interviews in many ways. Jake and Max, environmental educators at the undergraduate and secondary levels respectively, talked about the sustainability lens (deeply steeped in systems approaches to knowledge) as a way of integrating knowledge about natural, social, and economic systems. Emmett asked, "How do we bring the modes of thinking from say philosophy and politics and design and research together? I mean that stands a chance anyway, of addressing some big issues in ways that we're not doing."

In several cases, participants expressed an integrated view of humans in the natural world. Jake spoke about "the emotional relationships that are at work in the human-ecological system. So not just kind of humans and fuzzy brown creatures, but also human-to-human interactions, humans and trees, trees and animals, that sort of thing." He talked about using his research and teaching to explore how "to build these emotional relationships so that people at least are more mindful of the systemic effects of their actions." From an anthropologist's perspective, Ethan said, "Western society still has this idea of being above nature, this idea that it's something for us to use and control. That's dangerous. . . . We are a part of the ecosystem just like anything else." (Systems literacy components: 1.2, 2.1, 2.2, 3.1, 3.2)

I2. Integrating Through Tension

Much of our modern educational system pulls against integration. Most often, disciplines are taught in isolation, and within each discipline, knowledge is reduced further. Discussing research in the social sciences, Noah explained,

> There is a logic of reductionism that pervades everything we do. You have to reduce things to some extent in order to publish something or to have an argument or model. It cannot just be infinite complexity and, you know, unintelligible interaction in complexity. And so I think there's a real tension in figuring out what is the appropriate balance between complexity and reductionism.

Similarly, Elizabeth described the tension inherent in integrating formal academic knowledge and more intuitive, natural ways of knowing. "You know," she wondered, "is systems literacy sometimes a little bit of a struggle?"

In some cases, participants spoke of the trade-off between specializing in a single, specific field (often the easier path to publishing and success in academia) versus drawing from many different domains in the role of a generalist and integrator. Montuori (2015) wrote about the challenge of finding a doctoral program to suit his "omnivorous" intellectual nature (p. 171). Integrating pulls against classification, blurring lines, evolving structures (if ever-so-slowly). William said,

> Everyone wants to call you, you know, they need to call you an applied mathematician or a computer scientist or a statistician. Really, I feel like we've come back to this point where we can be more like the Renaissance. It's really exciting. It's super exciting.

(Systems literacy components: 1.2, 2.1, 2.2, 3.1, 3.2, 3.3)

I3. Integrating Through Narrative

Though William's academic home is in the department of math and statistics, his intellectual interests range far beyond what a lay audience might consider the boundaries of that domain. In his interview, he expressed an enthusiastic interest in "the whole thing

. . . the Big Bang all the way through." He described being especially drawn to language and discussed the power of stories to connect ideas across contexts. "I think stories are kind of the big piece," he said. The idea of the narrative form for integration and explanation came up several times. Noah talked about teaching his political science students the genre of analytic narrative to weave together ideas like structure and agency, to think about relationships, emergence, and long-term change. "If you're really trying to construct some sort of evolutionary narrative or narrative using complexity theory," he said, "I think it's much more sort of historical in nature. It's much more of an analytic narrative." He talked about integrating quantitative data into such narratives to inform them "in a rigorous way." Ogilvy (2015) wrote about the power of the narrative form in playing out alternative scenarios: "The story form provides a larger container for the many pieces of a complex puzzle to come together in a way that is both intelligible and communicable" (p. 13). Narrative, it seems, has great potential for making sense out of complexity. (Systems literacy components: 2.2, 2.3, 2.4)

I4. Learning, Integrating, Adapting, Evolving

The process of integration is iterative, ongoing, and adaptive. Integrating knowledge across disciplines, contexts, and experiences changes not only the knowledge but also the knower. Montuori (2015) wrote,

> The implications of complexity and transdisciplinarity go far beyond a set of tools for academic inquiry. They call for a reflection on who we are, how we make sense of the world, and how we might find ways to embody different ways of being, thinking, relating, and acting in the world. (p. 184)

Elizabeth framed the concept of agile learners, like other complex adaptive systems, as systems that are "never finished, because the ground on which they are located is constantly shifting and changing and they're constantly changing and adapting to whatever's happening. . . . A good learner," she said, "an adaptive being." (Systems literacy components: 3.3)

Developing a Systems Lens

D1. Learning the Culture (i.e., Language, Literature, History) of Complexity

Through grounding, questioning, broadening, and integrating, one can be sensitized to complex systems and develop, without ever learning the specific vocabulary, what Nick, a professor of community development and applied economics, described as "a lay appreciation of the complexity that we face." Several participants spoke of learning about complexity indirectly first through studying subjects like biology and ecology. Ben said of his own early studies, "It wasn't called systems, but it's biology, and you can't avoid talking about systems when you're talking about biological realities." Madeline, a biochemical engineer, made the point that, though she had only been exposed to the language of complex systems within the past several years, in retrospect she saw that she "was definitely doing complex systems research before that."

As William said, “Many people inherently are working on complex phenomena, of course. They don’t need to frame it like that.” And yet the lens is useful. “We live in this complexity,” Nick explained, “and I think we’re fishing for a cognitive framework to understand it, and I think complex systems lenses provide us with that.” When we give people tools to label and describe complex phenomena, he said, “light bulbs go on.”

Just as there is not one language of complexity, there is not one valid way of developing a systems lens. And yet, to be systems literate, one must have access to the language and meaning of complexity. At its most basic level, this means having, as Jake put it, “an understanding of what that word even means and how it affects things, so if you say, ‘This system is complex,’ a very reasonable answer is ‘so what? So what does that actually mean in terms of its behavior?’” Developing a systems lens grounded in one or more of the overlapping branches of complexity studies (e.g., systems thinking, system dynamics, chaos theory, complexity theory, agent-based modeling, etc.) gives one an analytic and synthetic framework for answering that question. (Systems literacy components: 1.1, 1.2, 1.3, 2.1)

D2. Developing a Systems Lens Through Formal and Informal Education

Though the concept of complexity is now several decades old, there remain relatively few courses and programs teaching about it directly. Some participants did talk about being exposed to a particular branch of complexity or a specific complex systems method in their graduate studies. Alex studied chaos theory as a graduate student in math. Ben used system dynamics modeling tools in some of his coursework and research in genetics. Noah talked about coauthoring papers with a doctoral advisor exploring complexity-related theoretical frameworks, especially evolutionary theory in the context of social and political change. But generally speaking, participants picked up their systems knowledge informally and in pieces along a long educational path. Some described early exposure to an article or book in the body of complexity literature that they found themselves circling back to several years later. Many described learning over time through reading widely, attending lectures, participating in workshops, and collaborating with colleagues to develop new skills. (Systems literacy components: 1.1, 1.3, 2.1, 3.1, 3.3)

D3. Refining the Systems Lens Through Modeling and Experimentation

Forrester (2007) argued that “systems thinking is a sensitizer” but that building and running computer simulations allows us to test our thinking and reveal inconsistencies in our mental models (p. 355). And though it is common knowledge within the world of complex systems that “all models are wrong” (Sterman, 2002, p. 501), modeling rigorously and iteratively is a way to deepen one’s understanding of the particular system being studied and to refine one’s systems lens. There were notable exceptions, but for the vast majority of participants, computers were central to their work with and/or understanding of complexity. Noah talked about the story of complexity being one of data and computational methods of analyzing it finally catching up with the sorts of theoretical questions that scholars have asked for generations. Byrne (2014) echoed this sentiment.

> Although the idea of emergence predates the development of digital computing by nearly a century, it is the development of that technology which provides us with tools which enable us to both data mine, explore enormous amounts of quantitative and now qualitative descriptions of what is and how it has come to be as it is, and simulate, construct artificial worlds which if calibrated on reality allow us to explore possibilities for the future development of reality. (p. 45)

Through modeling, simulating, and experimenting, participants tested their assumptions and refined their systems lenses over time. Elizabeth reflected, “I think that the lens is something that’s never finished. I think it keeps developing as long as somebody continues to actively engage in understanding more fully.” (Systems literacy components: 1.2, 1.3, 2.2, 2.3, 2.4, 3.2, 3.3)

Table 5

Components of Systems Literacy Aligned with Processes of Becoming

Theme	Grounding			Questioning				Broadening		Integrating				Developing a systems lens		
Text Section	G1	G2	G3	Q1	Q2	Q3	Q4	B1	B2	I1	I2	I3	I4	D1	D2	D3
Systems literate individuals . . .	CULTURAL DIMENSION															
(1.1) know the context and language of complex systems														●	●	
(1.2) read the world through a systems lens	●	●	●						●	●	●			●		●
(1.3) comprehend self-organization and emergence														●	●	●
	OPERATIONAL DIMENSION															
(2.1) cross disciplinary boundaries		●	●					●	●	●	●			●	●	
(2.2) employ scientific inquiry and empirical methods	●	●	●	●	●		●			●	●	●				●
(2.3) work to understand nonlinear change	●			●								●				●
(2.4) activate multiple modes of communication		●							●			●				●
	CRITICAL DIMENSION															
(3.1) pursue multiple perspectives		●		●	●	●	●	●	●	●	●				●	
(3.2) recognize the power of mental models	●			●	●	●				●	●					●
(3.3) engage in active, adaptive learning	●	●		●		●	●	●	●		●		●		●	●

Discussion

The first four processes described above—*grounding*, *questioning*, *broadening*, and *integrating*—can play out independently of *developing a systems lens*. One can build depth and breadth of knowledge, the critical capacity to question and evaluate that knowledge, and the intuitive and creative capacity to see and make connections without ever learning the language of complexity. So why add that lens?

The systems lens serves as a connective thread tying the other four together such that each can reinforce the others. It lends a vocabulary and series of explanatory patterns to the connections a learner sees intuitively when she is deeply grounded in a particular community or body of knowledge. It offers a concrete framework for asking challenging questions about that community or body of knowledge. A person who is both grounded and curious is likely, as Meadows and Wright (2008) suggested, to "follow a system wherever it leads" (p. 200) broadening her education across disciplinary divides and beyond school walls in search of answers. Finally, the systems lens is a powerful tool for integrating bits and pieces of wisdom picked up from many places and diverse perspectives along that journey of exploration. Olds (2015) wrote, "In systems perspective, intellectual autobiography becomes a story of resonances, tracing a set of predisposing themes through the levels of one's life and work that eventually find emergent voice and congruence in systems models" (p. 17). The systems lens can guide and frame cycles of grounding, questioning, and broadening. And especially through the reflective practice of integration, an individual continues to refine her systems lens over time.

The pattern of becoming systems literate is presented above in a fairly linear way, but of course, complex, adaptive learning is not linear. It is messy. This simplified narrative of becoming systems literate, if reframed in terms of iterative and overlapping cycles, illustrates a core understanding about what Green (2012) described as "the relationship between learning literacy and learning *through* literacy": Learning literacy, he explained, "involves the development of reading and writing abilities, or literacy capability—how children become (more) literate"; learning *through* literacy "concerns the notion of literacy as a specific tool for learning. On the one hand, literacy is conceived as the goal of schooling; on the other, it is the means of schooling" (p. 11). Figure 2 below recasts the more linear logic implied above in terms of iterative, adaptive learning to demonstrate the overlapping, often simultaneous nature of all five processes. The star at the center represents the point at which knowledge and experience synthesized might best inform action in a complex world.

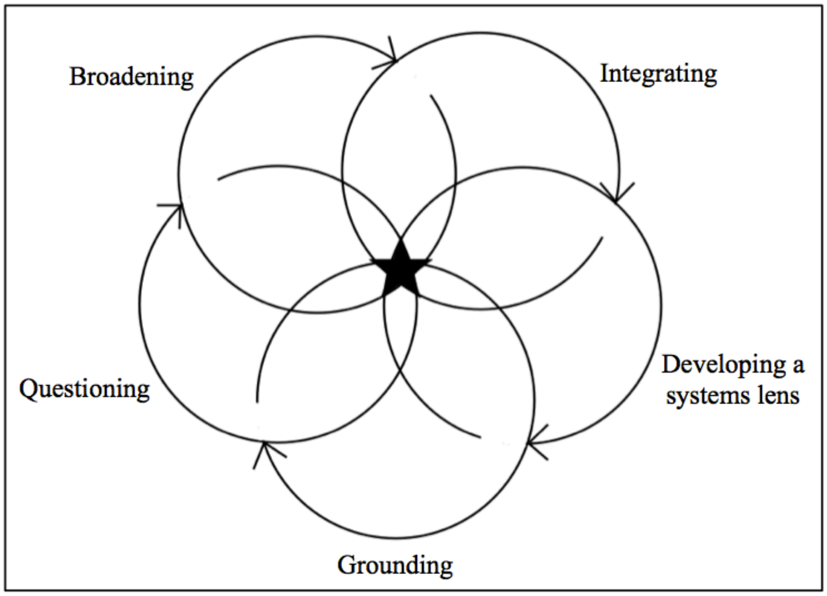

Figure 2. **Simultaneous and overlapping cycles of becoming.**

Systems Literacy in K-16 Education

It is worth noting that much of what is presented here is not new. There are already many effective educational practices for helping students to develop a deep *grounding* in their local communities and eco-systems. Place-based, experiential, and food-systems education come immediately to mind. But more traditional models of education remain relevant inasmuch as they can ground students in domain-specific knowledge, building a solid foundation by developing the cultural, operational, and critical dimensions of literacy in any specific subject.

Excellent educators have always worked to develop students' critical thinking skills and their capacity to ask and explore challenging, open-ended *questions*. Systems thinking and system modeling strategies offer structure to that challenging task (see, e.g., Richmond, 1993), and systems literacy as a concept reinforces the goal. Distribution requirements in high school and college serve the purpose of *broadening* students' exposure to different ideas and modes of inquiry. And though complex systems are perhaps most often associated with the hard sciences, math, and computers, this extended exploration of what it means to be and to become truly systems literate presents a solid defense of arts integration, language learning, and a liberal arts approach to education in general. Exploring all of the ways that the current education system promotes systems literacy is beyond the scope of this article, but it is undoubtedly the case that there are many such connections to be made and nurtured.

And yet, the traditional education system typically falls short in supporting two of the processes outlined above: *integrating* and *developing a systems lens.* Proponents of systems thinking education have often pointed to the "fragmented" and "compartmentalized" nature of education (Fisher, 2011; Forrester, 2007; Marshall, 2006; Sweeney & Sterman, 2007; Wessels, 2006) especially in the contexts of secondary and undergraduate level curricula. If we want to develop systems literate learners, we must not only provide more integrated, inter- and transdisciplinary courses and learning opportunities, but also support students in developing a systems lens to continue making such connections for themselves.

Forrester (2007) argued, "The systems viewpoint is a paradigm, a frame of reference, a way of looking at one's surroundings, that takes a long time to internalize, probably several years" (p. 356). He advocated for early and ongoing exposure to the language and methods of systems. This article serves as a contribution to the conversation of how that work might be done.

References

Ackoff, R. L. (1997). Systems, messes and interactive planning. *The Societal Engagement of Social Science*, *3*, 417-438.

Bennett, L. & Sweeney, L. B. (n.d.). If you cut a cow in half, do you get two cows? Center for Ecoliteracy. Retrieved February 19, 2015, from http://www.ecoliteracy.org/essays/if-you-cut-cow-half-do-you-get-two-cows

Betts, F. (1992). How systems thinking applies to education. *Educational Leadership*, *50*(3), 38–41. doi:10.1579/0044-7447

Burneko, G. (2015). The starry night sky. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 32-48). New York, NY: Routledge.

Byrne, D. (2014). Thoughts on a pedagogy of complexity. *Complicity: An International Journal of Complexity and Education, 11*(2), 40-50. Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/view/22963

Byrne, D. & Callaghan, G. (2014). *Complexity theory and the social sciences: The state of the art.* New York, NY: Routledge.

Charmaz, K. (2000). Grounded theory: Objectivist and constructivist methods. In N.K. Denzin & Y.S. Lincoln (Eds.), *Handbook of qualitative research* (p. 509-535). Thousand Oaks, CA: Sage Publications.

Cloud, J. P., ed. (2012). Education for sustainability: EfS standards and performance indicators. The Cloud Institute for Sustainability Education. Retrieved from http://cloudinstitute.org/cloud-efs-standards/

Combs, A. L. (2015). My life in chaos. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 72-92). New York, NY: Routledge.

Conklin, J. (2009). *Building shared understanding of wicked problems*. Interview with Christensen, K. *Rotman Magazine*, the alumni magazine of Rotman School of Management. Retrieved from http:// www.cognexus.org/Rotman-interview_SharedUnderstanding.pdf

Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Los Angeles, CA: Sage Publications.

Creswell, J. W. (2013). Qualitative inquiry and research design: Choosing among five traditions (3rd ed.). Thousand Oaks, CA: Sage Publications.

Denzin, N. K., & Lincoln, Y. S. (2000). *Handbook of qualitative research*. Thousand Oaks, Calif: Sage Publications.

Dubberly, H. (2014). A systems literacy manifesto. In *Proceedings of RSD3, Third Symposium of Relating Systems Thinking to Design*. Oslo, Norway: Oslo School of Architecture and Design, October 15-17, 2014. Retrieved from http://systemic-design.net/wp-content/uploads/2014/08/Hugh_Dubberly_systems_manifesto.pdf.

Eisler, R. (2015). Human possibilities: An integrated systems approach. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 93-113). New York, NY: Routledge.

Fisher, D. M. (2011). "Everybody thinking differently": K–12 is a leverage point. *System Dynamics Review*, *27*(4), 394–411. doi:10.1002/sdr.473

Forrester, J. W. (2007). System dynamics—a personal view of the first fifty years. *System Dynamics Review*, *23*(2-3), 345–358. doi:10.1002/sdr.382

Forrester, J. W. (2009). Learning through system dynamics as preparation for the 21st century. Sloan School of Management. Massachusetts Institute of Technology. Retrieved from http://www.clexchange.org/curriculum/complexsystems/complexsystems_resources.asp

Geert, P. V., & Steenbeek, H. (2014). The good, the bad and the ugly? The dynamic interplay between educational practice, policy and research. *Complicity: An International Journal of Complexity and Education*, *11*(2). Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/view/22962

Goerner, S. J. (2015). Bringing forth that which is within: How an invisible hand led me to a life that "feels like my own." In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 156-169). New York, NY: Routledge.

Grauwin, S., Beslon, G., Fleury, É., Franceschelli, S., Robardet, C., Rouquier, J.-B., & Jensen, P. (2012). Complex systems science: Dreams of universality, interdisciplinarity reality. *Journal of the American Society for Information Science and Technology*, *63*(7), 1327–1338. doi:10.1002/asi.22644

Green, B. (2012). Subject-specific literacy and school learning: A revised account. In Green, B. & Beavis, C. (Eds.), *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Green, B., & Beavis, C. (2012). *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Linden, K.V. (2006). A grounded approach to the study of complex systems. *World Futures, 62*(7), 491-497. doi:10.1080/02604020600912806

Low, A. (2015). Introduction: The complexity of life and lives of complexity. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 1-3). New York, NY: Routledge.

Manson, S. M. (2001). Simplifying complexity: a review of complexity theory. *Geoforum*, *32*(3), 405–414. doi:10.1016/S0016-7185(00)00035-X

Marshall, S. P. (2006). *The power to transform: Leadership that brings learning and schooling to life*. San Francisco, CA: Jossey-Bass.

Meadows, D. H., & Wright, D. (2008). *Thinking in systems: A primer*. White River Junction, VT: Chelsea Green Publishing.

Mitchell, M. (2009). *Complexity: A guided tour*. New York, NY: Oxford University

Press.
Montuori, A. (2015). Complexity and transdisciplinarity: Reflections on theory and practice. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 170-200). New York, NY: Routledge.
Morgan, G. (2006). *Images of organization.* Thousand Oaks, CA: Sage Publications.
National Council for the Social Studies (NCSS). (2013). The College, Career, and Civic Life (C3) Framework for Social Studies State Standards: Guidance for Enhancing the Rigor of K-12. Silver Spring, MD: NCSS. Retrieved from http://www.socialstudies.org/system/files/c3/C3-Framework-for-Social-Studies.pdf
NGSS Lead States. (2013). *Next Generation Science Standards*: For states, by states; Appendix A: Conceptual shifts in the *Next Generation Science Standards*. In *A Framework for K-12 Science Education: Practices, crosscutting concepts, and core ideas*. Washington, DC: Achieve, Inc. Retrieved from http://www.nap.edu/catalog.php?record_id=13165
Ogilvy, J. (2015). Systems theory, arrogant and humble. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 4-16). New York, NY: Routledge.
Olds, L. E. (2015). Systems patterns and possibilities. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 17-31). New York, NY: Routledge.
Patton, M. Q. (2002). *Qualitative research and evaluation methods*. Thousand Oaks, CA: Sage Publications.
Patton, M. Q. (2011). *Developmental evaluation: Applying complexity concepts to enhance innovation and use*. New York: Guilford Press.
Plate, R. R. (2006). *Assessing the effectiveness of systems-oriented instruction for preparing students to understand complexity.* (Doctoral dissertation). The University of Florida. Retrieved from http://www.clexchange.org/resources/research.asp
Plate, R., & Monroe, M. (2014). A structure for assessing systems thinking. *The Creative Learning Exchange*, *23*(1), 1-6. Retrieved from http://www.clexchange.org/ftp/newsletter/CLEx23.1.pdf
Richmond, B. (1993). Systems thinking: critical thinking skills for the 1990s and beyond. *System Dynamics Review*, *9*(2), 113-133. doi:10.1002/sdr.4260090203
Rogers, M., Pfaff, T., Hamilton, J., & Erkan, A. (2013). Incorporating sustainability and 21st-century problem solving into physics courses. *The Physics Teacher*, *51*(6), 372. doi:10.1119/1.4818380
Sahtouris, E. (2015). A passion for pushing the limits. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 49-71). New York, NY: Routledge.
Shelburne Farms' Sustainable Schools Project. (2011). The guide to education for sustainability. Shelburne, VT: Shelburne Farms.
Senge, P. M. (2012). Creating schools for the future, not the past for all students. *Leader to Leader*, (65), 44–49. doi:10.1002/ltl.20035

Shenton, A. K. (2004). "Strategies for ensuring trustworthiness in qualitative research projects." *Education for Information*, *22.* 63-75. Retrieved from http://search.ebscohost.com.ezproxy.uvm.edu/login.aspx?direct=true&db=aph&AN=13857302&site=ehost-live

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review, 18*(4), 501-531. doi:10.1002/sdr.261

Stillman, S. (2006). Grounded theory and grounded action: Rooted in systems theory. *World Futures, 62*(7), 498-504. doi:10.1080/02604020600912830

Sweeney, L. B. (n.d.). Thinking about systems: 12 habits of mind. Linda Booth Sweeney. Retrieved from http://www.lindaboothsweeney.net/thinking/habits

Sweeney, L. B. (2009). Systems teaching and farm-based education. Reprinted in Farm Based Education Network. (n.d.). Retrieved February 19, 2015, from http://www.farmbasededucation.org/page/systems-teaching-and-farmbased

Sweeney, L. B. (2014). Learning to connect the dots: Developing children's systems literacy. CLEx23.2.pdf. Spring 2014. 1-12.

Sweeney, L. B., & Meadows, D. (2010). *The systems thinking playbook: Exercises to stretch and build learning and systems thinking capabilities*. White River Junction, VT: Chelsea Green Pub.

Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review*, *23*(2-3), 285–311. doi:10.1002/sdr.366

Toscano, P. M. (2006). The study of global solutions: A postmodern systems thinking view of grounded theory/grounded action. *World Futures: The Journal of New Paradigm Research, 62*(7), 505-515. doi:10.1080/02604020600912848

Umphrey, S. (2002). *Complexity and analysis*. Lanham, MD: Lexington Books.

Waters Foundation. (2014). Habits of a systems thinker. Systems Thinking in Schools. Retrieved from http://watersfoundation.org/systems-thinking/habits-of-a-systems-thinker/

Wessels, T. (2006). *The myth of progress: Toward a sustainable future.* Burlington, VT: University of Vermont Press.

Photomosaic possibilities: Developing a systems lens to inform education redesign

Complex systems are ubiquitous, the concept of complexity is widespread and well developed in academia, and systems theorists have developed sophisticated understandings of how such systems (animals, eco-systems, organizations, communities, etc.) adapt and evolve to changing contexts and constraints. However, our collective practice as a society does not consistently reflect twenty-first century understandings of complexity. This article argues that to prepare society to solve interconnected challenges across environmental, economic, and social systems in the years ahead, our K-12 schools must prepare systems literate citizens. The author summarizes an extended study that resulted in a robust definition of systems literacy and a grounded theory of how one becomes systems literate. In discussing implications of this study, she argues that a powerful leverage point for adapting schools to develop systems literacy among students is developing a systems lens among teachers and education leaders.

Keywords: Systems literacy; curriculum; pedagogy; leadership; school change

Introduction—A call for systems literate citizens

We are living in an era of growing economic disparity, heightened racial and religious conflict (exacerbated by vitriolic political discourse), and increasing migration in response to environmental and political collapse. Interconnected problems like these are what systems theorists have referred to as *system messes* (Ackoff, 1997; Denning, 2007), *wicked problems* (Churchman, 1967 cited in Byrne, 2014; Conklin, 2009; Denning, 2007), or simply *21st century problems* (Rogers, Pfaff, Hamilton, & Erkan, 2013). Such challenges exist at the intersections of local and global societies, ecosystems and "anthropo-systems"; they exist across space-scales—"from the local to the planetary"—and time-scales—"from the short to the very long term" (Kagan, 2010, p. 1,094). They are definitively *complex.* Over the last several decades, one thing that has become increasingly clear is that environmental, economic, and social justice issues are intertwined. This is a basic assumption of the sustainability movement (see, e.g., Alperovitz, Speth, & Guinan, 2015; Kagan, 2010; Stafford et al., 2010), but the need to understand complexity arising out of interdependent, nested complex systems is not only a 'green' phenomenon.

Across contexts, the capacity to identify, interpret, and grapple with complex realities has been identified by various names. Byrne and Callaghan (2014) referred to it as the *complexity frame of reference*. Capra and Luisi (2014) called it *the systems view of life*. Sweeney (2014) called it *systems literacy.* Using that language, Dubberly (2014) argued that a lack of capacity among leaders to make effective decisions in the contexts of interdependent complex systems 'is not stupidity. It is a sort of illiteracy. It is a symptom that *something is missing* in public discourse and in our schools' (p. 2).

In recent years, many writers have advocated redeveloping our school curricula through a systems lens (e.g., Betts, 1992; Cassell & Nelson, 2010; Fisher, 2011; Senge, 2012; Sweeney & Sterman, 2000, 2007). Metz (2012) argued, 'It's crucial that students learn the habits of systems thinkers in order to solve our most intractable problems—

poverty, hunger, war, ignorance, resource depletion, and environmental degradation, among many others' (p. 6). Cassell and Nelson (2010) advocated for 'the creation of an expanded interdisciplinary curriculum that reflects a genuine sense of the interconnectedness of life and the importance of place in a complex global system of reciprocal interdependence' (p. 179).

In most schools though, the current content and structure of K-12 curricula do not reflect the complexity of contemporary society, its economy, or the environment within which those systems function, nor do schools prepare students well to grapple with complex realities at the intersections of traditionally disparate fields. A forward looking approach to education must help students not only to learn and retain foundational curricular knowledge and skills, but also to make connections between the subjects they study in school, between school and the world around them. Schools must help students develop systems literacy to prepare them solve complex problems, to innovate, to engage, and to flourish in changing times. However, reimagining schools in this way is especially challenging because most of today's educators are products of an education system that did not support them in developing these capacities themselves.

Before we can redesign K-12 education to support developing *students'* systems literacy, we must build capacity for such change among *teachers* and *school leaders*. To that end, this article discusses a grounded theory study to develop a detailed definition of systems literacy and a working theory of how one becomes systems literate. That work is summarized in section two below. Section three turns toward implications of the study's findings, arguing that a key leverage point for educational change is supporting educators in developing a systems lens through which to rethink curricula, pedagogies, and school practices. Section four addresses a few complexity-informed perspectives on organizational change and presents the metaphor of a photomosaic to discuss the potential for diversity and emergence to inform innovation in an education system reimagining itself for changing times.

A grounded theory study of systems literacy for K-12 education

Systems thinking, system dynamics, complex systems science, and complexity theories represent a few of the many modern approaches to grappling with complex realities in research and practice. There are important distinctions between each of the branches of complexity. Some are highly quantitative in nature, deeply rooted in math, statistics, and computer science. Others are more qualitative, focusing on description and the power of the narrative form. Some emphasize human systems, social systems, organizational systems, etc. Some focus on the organic systems at the heart of biology and ecology. Each represents a way of thinking about, studying, and engaging in the world that is in line with a basic understanding of interdependence, self-organization, emergence, and complexity. Each approach transcends traditional disciplines and domains of practice. This study focused on the common themes among them to explore ways in which this body of methods and ideas might inform K-12 education in changing times. The open-ended exploration led to the phenomenon of systems literacy and a theory (grounded in data from texts and interviews) of how one becomes systems literate.

Research design

Using grounded theory methods (see, e.g., Byrne & Callaghan, 2014; Corbin & Strauss, 2008; Creswell, 2013; Linden, 2006; Stillman, 2006; Toscano, 2006), I interviewed 22 academics and educators from twelve different institutions. Participants included three middle and high school teachers of social studies, science, food systems, and sustainability; three professional developers who work with K-12 and college educators; and sixteen professors in fields ranging from computer science and electrical engineering, to political science, anthropology, public administration, and classical studies. All participants had one thing in common. Each one employs complexity-informed concepts and methods in his or her research and/or instruction. In addition to these 22 transcribed interviews, I analyzed seventeen texts as data sources to answer two central research questions: *What is systems literacy?* and *How does one become systems literate?*

The questions and answers alike emerged out of an extended, iterative research process. Starting with a pilot study and only three participants, I used interviews to explore common themes among people studying and teaching about complexity across different disciplines and contexts. Scaling that study up, I interviewed fifteen more participants to uncover a series of skills and dispositions for grappling with complexity. The work resulted in a detailed list of nine preliminary findings (e.g., 'the ability to see connections between subjects and ideas,' 'the ability to curate, manage, and analyze . . . data,' etc.) (see Author, 2015). A return to the literature surfaced the core concept—systems literacy—and the research questions above guided data collection and analysis going forward. I have shared findings with twelve of the 22 participants at various points and engaged in extensive comparative analysis to revise and fine-tune my interpretations along the way (Corbin & Strauss, 2008; Shenton, 2004). More detailed descriptions of my research process are provided in previous articles (Author, under review a&b). Findings from each of those articles are summarized briefly below.

Defining systems literacy

The *Literacy in 3D* model, as presented by Green (2012), offered a framework to structure a working definition of systems literacy. The model outlines a particularly active form of subject-specific literacy, emphasizing production over consumption of knowledge and active forms of communication (especially but not limited to writing) over passive forms (as in reading, viewing, etc.). The '*3D*' in the model's name refers to three interdependent dimensions of subject-specific literacy—the cultural, operational, and critical dimensions (Green & Beavis, 2012). The following definition emerged from an analysis of 22 interviews along with five texts and online resources delineating knowledge and skills associated with systems thinking and systems education (Dubberly, 2014; Plate & Monroe, 2014; Richmond, 1993; Sweeney, n.d.; Waters Foundation, 2014).

In the context of systems literacy, one who is culturally literate is well versed in the language and context of at least one branch of complexity studies (e.g., systems thinking, chaos theory, etc.). She reads the world (in the Freirean sense, see Freire, 1985) through a systems lens and is inclined toward synthesis and holism understanding each in terms of self-organization and emergence. From this perspective, she sees and makes connections between disparate subjects, ideas, and contexts.

One who is operationally literate has developed the skills of communication required to produce and convey meaning within the culture of systems literacy. She crosses disciplinary boundaries to, as Meadows and Wright (2008) wrote, 'follow a system wherever it leads' (p. 200). She explores new ideas through the process of scientific inquiry, rooting her evolving understandings in empirical evidence. She acknowledges and seeks to understand and affect nonlinear change, and she employs varied modes of communication to structure her thinking as she constructs and shares new understandings.

In the context of systems literacy, a critically literate individual questions and refines her knowledge and skills, recognizing the power of mental models to shape her view of the world (and the views of others), actively seeking multiple perspectives to avoid polarized thinking and deepen understanding, and engaging in active, adaptive learning. For these reasons, a systems literate individual is well prepared to grapple with problems and design solutions and innovations at the intersections of interdependent complex systems. (For a more detailed definition, see Author, under review a.)

Becoming systems literate

Grounded theory methods are well suited to developing not only descriptions of concepts (as in the dimensions of systems literacy summarized above) but especially to identifying patterns and processes. For this reason, grounded theory was a good methodological fit for my second question: *How does one become systems literate?* To answer this question, I reanalyzed the 22 transcribed interviews along with twelve articles in which authors described their own paths to complexity (Burneko, 2015; Byrne, 2014; Combs, 2015; Eisler, 2015; Forrester, 2007; Goerner, 2015; Low, 2015; Montuori, 2015; Ogilvy, 2015; Olds, 2015; Sahtouris, 2015; Sterman, 2002). Of course, each of these 34 stories was unique, but five important patterns emerged. The overall process, though nonlinear, iterative, and messy, can be summarized briefly by the words and phrases *grounding*, *questioning*, *broadening*, *integrating*, and *developing a systems lens.*

Grounding can refer to a deep connection to the natural world or a firm rooting in a community or the world of work. A particularly common theme across interviews and essays was grounding in agricultural and food systems. In this context, natural systems are in close contact with manmade economic, social, and cultural systems. A few participants and authors described how experiences at these intersections illuminated the concrete implications of system failings or challenged them to develop the creative capacities to 'make do' within material limitations. But *grounding* does not only refer to having one's feet planted firmly in physical systems. It can also refer to being deeply grounded in one or more disciplinary areas. Domain expertise lends one not only credibility in collaborating to tackle interdisciplinary systems questions but also a foundation of knowledge and examples to draw from when interpreting new information.

A second major theme illustrating the process of becoming systems literate is *questioning.* Participants discussed grappling with big, open-ended questions—questions without simple or singular answers. Some questioned established methodologies and ontologies (ways of studying and ways of knowing); some highlighted the need to question mental models (the often-implicit assumptions that affect how we view the world around us). Some questioned particular social and economic structures as they studied or designed alternative solutions to contemporary problems (e.g., questioning rampant consumerism, questioning energy use patterns). Grappling with hard-to-answer questions and rooting emergent answers in empirical evidence seems to instill in systems literate individuals a capacity to embrace ambiguity, uncertainty, and continual change.

The concept of *broadening* was the first to emerge from essays and interviews alike. Participants and authors described having very broad educational backgrounds. Some described exploring a wide range of fields through a liberal arts degree; some described switching majors multiple times or earning multiple degrees in loosely related or seemingly unrelated fields of study. Many described not fitting well within any one traditional academic niche. Beyond formal education, participants also described independent and collaborative learning experiences (e.g., attending lectures and workshops, reading widely, teaming up across disciplines, and engaging with experts outside the world of academia to tackle real-world problems) through which they developed some of the skills and knowledge at the heart of their work with complexity. A broad educational background (both formal and informal) provides opportunities to consider multiple ways of thinking about an issue and see connections between ideas that are sometimes hidden behind disciplinary walls.

Such connections become meaningful through the process of *integrating* knowledge. Participants emphasized bringing together insights and skills from disparate fields to tackle problems, find solutions, and advance knowledge in their own areas of expertise. Many demonstrated what Olds (2015) called an 'and/also' rather than 'either/or' approach to developing understandings (p. 18). Some spoke of drawing together multiple, legitimate though conflicting perspectives in exploring real-world scenarios. Some explained efforts to support students in synthesizing knowledge from various fields. Several described the central role of the generalist versus specialist perspective in complexity studies. Integrating new knowledge, especially contradictory or conflicting knowledge, is a transformative process. As one participant said, 'A good learner is an adaptive being.'

Though it is easy to construct a linear narrative of *grounding*, *questioning*, *broadening*, and *integrating* in that order, reflective and adaptive learning is actually a messy, iterative process. Furthermore, the process of *developing a systems lens* can occur at any point in a circuitous trajectory. Developing a systems lens involves learning the language of complexity based in one or more of the various fields of complexity studies (e.g., systems thinking, system dynamics, chaos and complexity theory, evolutionary theory, etc.). It involves being grounded in the literature, history, and practice of complexity. Because the concept of complex systems has emerged in a wide range of fields over the last half century (and in many cases much longer), there is not a single canon of complexity (Grauwin et al., 2012). There is no one systems lens. Rather, immersion in key complexity concepts in the social sciences, hard sciences, computer sciences, humanities, etc. (and especially exposure to related concepts across a range of fields) can provide one with foundational language and understandings framing a particular way of seeing the world (Byrne & Callaghan, 2014; Capra & Luisi, 2014). Thus *developing a systems lens* may be seen as a micro-process involving each of the others—*grounding*, *questioning*, *broadening*, and *integrating*—in itself, and a macro-process informing each of those in turn. (For a more detailed description of how one becomes systems literate and how each of these five processes align with the components of systems literacy summarized above, see Author, under review b.)

Implications

The knowledge and skills associated with systems literacy are not entirely new. For instance, many educators have long emphasized the importance of considering an issue from multiple perspectives, of grounding understandings in empirical evidence, of engaging in rigorous inquiry, among other components of systems literacy. Furthermore, many traditional and emerging education practices emphasize the processes of grounding (e.g., place-based education, food systems education, service learning), questioning, and broadening (e.g., liberal arts programs; distribution requirements; instruction in arts, languages, etc.). And yet, the education system as a whole does not consistently support the development of systems literate individuals. In particular, it tends to fall short in providing opportunities for students to integrate knowledge across disciplines and contexts and to develop a systems lens.

Though complex systems concepts have evolved over more than a half-century, and related research methods are well established in fields like genetics, physics, engineering, and various social sciences (see, e.g., Bar-Yam, Ramalingam, Burlingame, & Ogata, 2004; Mitchell, 2009; Byrne & Callaghan, 2014), the vast majority of complex systems instruction today occurs at the graduate level in education. Systems concepts are taught explicitly only in pockets at the undergraduate and K-12 school levels. Certainly, many teachers have had their own formative experiences of *grounding*, *questioning*, *broadening*, and *integrating*. But relatively few have been exposed to the vocabulary of complexity. Few have had the opportunity to *develop a systems lens* themselves. Though developing systems literacy among students may be essential for the future problem-solving capacities of our societies, teachers cannot be expected to teach what they do not know. As Cunningham (2014) argued, 'Teachers need to be educated to expect *more* from their students—more, indeed, than was asked of themselves. This is without question a wicked problem' (p. 105).

Rendering the problem wickeder still, for teachers who *are* already systems literate, the structures of our current school systems often impede the types of transdisciplinary collaboration required for authentic systems education. Too often today's educational policies emphasize a few discrete bodies of academic knowledge (reading, math, and science) over others, not only reifying the independent standing of each of these subjects, but also reducing the share of academic energy allocated to untested but deeply important subjects like civic participation, the arts, or the intersections of science and society. Today's overemphasis on high stakes testing distracts educators from other long-standing and equally valid educational goals, not least of which is preparing today's youth to perpetuate and improve the democratic ideals and processes that will be needed to address environmental and societal challenges in the years ahead.

There is much work to be done to adapt today's schools to develop systems literate citizens. Importantly though, there is not one right way to engage in that work. From a systems view, emphasizing diversity, experimentation, and emergent solution making to redesign education systems holds greater promise than applying pre-established solutions (Kania & Kramer, 2013; Patton, 2011). There do exist professional development organizations and opportunities, learning modules, and teaching tools to support teachers in developing their own and their students' systems skills and vocabularies (see Creative Learning Exchange, 2016; Fisher, 2011; Waters Foundation, 2014, 2016). Here I argue that we can strengthen what Kania and Kramer (2013) refer to as the 'collective impact' of such resources and inspire the development of many more by first emphasizing *developing a systems lens* among professional educators so that they might see their work in a new light.

Changing the way educators see the world

Changing the way educators see their work involves intervening with the system at the paradigmatic level (Meadows, 1999; Morgan, 2006; Senge, 1990, 2000, 2012). Meadows (1999) wrote, 'The shared idea in the minds of society, the great big unstated assumptions—unstated because unnecessary to state; everyone knows them—constitute that society's paradigm or deepest set of beliefs about how the world works' (p. 17). In the reigning educational paradigm, the belief that disciplines represent discrete bodies of knowledge serves as the foundation for what systems educators describe as a 'fragmented' and 'compartmentalized' curriculum (Fisher, 2011; Forrester, 2007; Sterman, 2002; Sweeney & Sterman, 2007). The belief that meaningful learning can be quantitatively assessed undergirds traditional grading systems along with the current culture of high stakes testing. The assumption that education is preparation for life is a central premise in documents like the *Common Core State Standards*, which emphasizes 'college and career readiness' over 'the essential goals of the arts, humanities, and sciences' and 'the immediate relevance of learning' (Tucker, 2011). These beliefs are mental models, ways of seeing the world, conventional not inevitable truths.

Many authors have emphasized the power of mental models to shape our understandings of what the world is and what it may become (e.g., Forrester, 2007; Morgan, 2006; Richmond, 1993; Sterman, 2002). Adopting a *complexity frame of reference* (Byrne & Callaghan, 2014), a *systems view of life* (Capra & Luisi, 2014), or what I refer to as a *systems lens*, is trying on a new mental model. Through a systems lens, one may recognize that disciplines are social constructions (see Green, 2012) without dismissing outright the value of such structures to organize and frame knowledge. Through a systems lens, one may acknowledge that not all worth learning can be measured without dismissing tests as irrelevant (albeit inherently limited) tools for measuring success. One might embrace the goal of education to prepare students for the future while acknowledging that for learning to stick, it must also be relevant now. A systems approach relies on an 'and/also' integration of knowledge, after all (Olds, 2015).

Photomosaic possibilities for innovation in educational design

Educators seeing the world through a systems lens holds great potential for educational transformation not because that lens provides a single, simple solution, but because it illuminates the power of diversity and emergent solution making. The artistic medium of photomosaic offers one way to understand the core complex systems concepts of *nestedness* and *emergence*. In a photomosaic, each individual photograph is nested within the larger image, and though any one image may be worthy of close observation—any one may tell a compelling story or raise a series of important questions—the observer cannot predict the cohesive image that will emerge from these many pictures by studying one in isolation. Likewise, in complex systems, the whole is not only *more* than the sum of its parts (Cunningham, 2014; Meadows, 2008; Wessels, 2006); it is also something entirely new, different, or *other* (Koffka, 2013; see also Anderson, 1972). The K-12 curriculum—constructed of people, places, perspectives, courses, projects, assignments, and experiences accumulated over the course of several years—is similar. Its potential value is inherently greater than and different from the simple sum of its parts. Thus each individual's cumulative educational experience is unique. Just as biodiversity is an essential attribute of resilient ecosystems (Kagan, 2010; Rockström et al., 2009; Wessels, 2006), learning diversity is central to robust and resilient education systems. Because emergent otherness is always a product of diversity and self-organization, prescribing a single approach to teaching for systems literacy would be counter-productive.

For instance, because complex systems are inherently inter- and transdisciplinary in nature, it might seem logical to claim that traditional mono-disciplinary courses are inferior. This is not necessarily true. Complexity does not reject reductionist traditions as much as it builds forward upon them through synthesis. To learn any one subject well, a student must look closely and study deeply. At the disciplinary level, systems concepts fit naturally within each of the sciences, and concepts learned within these disciplines transfer. Biological and ecological systems especially offer abundant metaphors for understanding manmade systems of many types. The computational thinking required by systems methodologies locates math in real world contexts too often missed by traditional pedagogical styles. A systems thinking approach to history would teach content fully contextualized, emphasizing connectivity and patterns of change over time. Interestingly, both the *Next Generation Science Standards* and the new *C3 Framework for Social Studies State Standards* emphasize systems lenses on disciplinary knowledge (National Council for the Social Studies, 2013; NGSS Lead States, 2013). Complexity theory in English courses could offer a new approach to analyzing and appreciating the human experience expressed through literature.

Of course, complex systems do offer myriad opportunities to pull the curricular pieces together, connecting history to science, literature to computation. Teaching the transdisciplinary themes of complexity and widely applicable complex systems methods in addition to traditionally disparate fields of knowledge would help students to see how the various subjects they learn in school are connected to one another and how school content connects to the world around them.

Importantly, in today's world of rapid and constant change, teachers cannot be expected to hold all the answers. Rather, they must model and teach processes for discovering and developing answers to new and changing questions. They must learn ahead of, with, and from their students. Supporting educators in developing a systems lens and reimagining their curricula and pedagogical practices through that shared worldview would be a powerful point of leverage for promoting a wide range of emergent innovations to teach toward systems literacy. As Cunningham (2014) explained, 'Having multiple perspectives increases the range of possibilities that can be imagined, and having diverse skills and abilities increases the likelihood that various possibilities can be realized' (p. 98).

Learning together

Teaching educators a systems lens is about asking them to see their world and their work in a new light. Such a process can create what Beabout (2012) identified as *turbulence*, 'the creation of increased uncertainty' (p. 16). He argued that responding to change and uncertainty is

> almost instinctively, a social process for humans. When we do not know what is coming next, we look at each other and ask, 'What's next?' This turning to each other without certainty is perhaps the pregnant seed of all social change. When current structures are in doubt, people engage with one another and make decisions together about what to do. (p. 17)

Beabout referred to the collaborative process of answering 'What's next?' within an organization as *perturbance* and argued that such work must be intentional and structured to be effective. Other systems theorists have outlined methods and approaches for organizational change emphasizing ideas like collaboration; iterative experimentation and research; and networking within and beyond school communities (see, e.g. Ackoff, 1997; Bryk, Gomez, & Grunow, 2011; Conklin, 2009; Snyder, 2013). Several have discussed the concept of double-loop learning, learning that is reflective and adaptive (e.g., Maani & Maharaj, 2004; Patton, 2011; Senge, 1990, 2000). Morgan (2006) wrote

> For successful double-loop learning to occur, organizations must develop cultures that support change and risk taking. They have to embrace the idea that in rapidly changing circumstances with high degrees of uncertainty, problems and errors are inevitable. They have to promote an openness that encourages dialogue and the expression of conflicting points of view. They have to recognize that legitimate error, which arises from the uncertainty and lack of control in a situation, can be used as a resource for new learning. They have to recognize that genuine learning is usually action based and thus must find ways of helping to create experiments and probes so that they learn through doing in a productive way. (p. 91)

Many authors have written about the concept of Learning Organizations (e.g. Beabout, 2012; Bryk, Gomez, & Grunow, 2011; Morgan, 2006; Senge, 1990, 2000, 2012). Their ideas and methods could guide school communities through the process of developing a systems lens among educators and operationalizing implications of systems literacy across the curriculum. Such collaborative, organization-wide learning is essential. Before we can expect students to develop a systems lens, teachers must do so. Before teachers can put such a lens to work in systemically redesigning curricula and pedagogy, school leaders must decide to support such change. 'Systemic change therefore requires involving all stakeholders in both understanding current approaches and why they need change, and in implementing new systems' (Cunningham, 2014, p. 73). Therefore, engaging at the paradigmatic level is likely to be most successful if professional educators—teachers and leaders alike—engage and learn together.

Focusing on complexity

How does one develop a systems lens? Primarily, by learning about complexity. *Complexity* sounds esoteric, which can make it seem irrelevant. Developing a systems lens, then, must start with highlighting how and why the complexity paradigm (emphasizing nonlinearity, interdependence, self-organization, and emergence) already impacts everyday life. Throughout the grounded theory study discussed above, several participants emphasized the need to teach complexity through examples. Flocks of birds, schools of fish, interdependent insect colonies displaying emergent behavior that could never be predicted by studying any one organism on its own—these examples and others like them are common in the literature of complexity (see, e.g., Wessels, 2006). Relevant examples abound in the natural world, and in the context of school change, the school system itself offers a series of examples of complexity in action.

Beyond real-time, real world examples, professional development could also include opportunities for educators to experience software for modeling and simulating complex systems. Study participants named various resources that could be useful in this work including programs like STELLA® and StarLogo and books like *An Introduction to Systems Thinking with STELLA* (Richmond & Peterson, 2001) and *Adventures in Modeling* (Colella, Klopfer, & Resnik, 2001). Playing with data to explore systems concepts like self-organization and emergence could not only support educators in learning the language and patterns of complexity, but could also support them in developing some of the computer skills (e.g., computational thinking and computer science principles) that their students will need to be fully literate citizens in years to come.

Book learning is relevant too. Study participants identified several books that informed their own early explorations of the world of complexity (e.g., *Never Cry Wolf,* Farley Mowat; *At Home in the Universe,* Stuart Kauffman; *Urban Dynamics,* Jay Forrester; *Thinking in Systems,* Donella Meadows; *Chaos: Making a New Science*, James Gleick; *The Tao of Physics*, Fritjof Capra; etc.). Some not mentioned by participants, like *Complexity: A Guided Tour* by Melanie Mitchell and *The Systems View of Life* by Fritjof Capra and Pier Luigi Luisi, offer detailed accounts of the history, geography, and current state of the field of complexity studies. Though these texts vary in terms of length and density, reading groups among educators would have no trouble finding opportunities to dig in to the literature of complexity. Perhaps more powerful than reading passively and alone, educators could collaborate together to synthesize learning by constructing narratives, building timelines, and mapping the evolution of thought across cultures and through time as complexity-informed contexts and innovations have emerged around the world. Through such collaborative learning, educators could construct together a shared systems vocabulary, a series of common examples, and an awareness of the ways in which complexity connects knowledge across disciplines and beyond school walls. They could build a common systems lens.

Professional development and the five processes of becoming systems literate

As described above, my research into systems literacy uncovered five core processes in becoming systems literate: *grounding, questioning, broadening, integrating,* and *developing a systems lens.* I have argued that this last one, developing a systems lens, must be central to preparing educators to teach about complex systems, because that lens is essential to connecting previous academic and life experiences through the context of complexity. But the other four processes could inform organizational learning for building and reinforcing systems literacy among educators as well.

Professional development funds often already support teachers and school leaders in learning opportunities to further ground themselves in their disciplines and domains of expertise. In the context of building systems literacy, this well-established allocation of time and money remains relevant. (It is not always as easy to find institutional funding to explore beyond one's core discipline, but the concept of broadening highlights the value of establishing new paths in learning.) The concept of grounding could also play out through professional development activities designed to ground educators in their local watersheds and communities. Educators who learn deeply about the natural and social systems in which their schools are nested will be better able to connect student learning opportunities to those natural spaces and community resources, to help students ground their learning in highly relevant, physical systems. School-wide conversations could emphasize questioning, especially critical and professionally relevant questions along the lines of *What do we teach and why? Whom do we teach? To what effect?* and *To what end?* Collaborating across disciplines and beyond school walls to answer these questions and others through professional learning activities could support educators in the processes of broadening and integrating knowledge. Such connections would lead to new questions.

Of course, if the goal is to develop a systems literate school community, all of this professional learning must be informed and reinforced through the process of developing a systems lens. Having developed that lens together, teachers and school leaders would share a common language and point of view through which to reimagine their work in schools and redesign their curricula and pedagogical approaches to correspond with the complexity inherent in the world around them.

Conclusion

In an increasingly complex and interconnected world, traditional, mono-disciplinary forms of instruction and assessment will not suffice to improve students' abilities to identify or develop effective solutions to complex social, political, and environmental problems even if by test results we deem those students to be college and career ready. Teachers and educational leaders cannot be content with teaching students snapshots of disconnected information. Rather, educators interested in school improvement as well as the authentic and meaningful education of today's students must think and teach with the big picture in mind.

Even as educators recognize the changing world around them and discuss the need for schools to keep pace, our school systems tend to recreate learning opportunities like those teachers experienced themselves (Fisher, 2011; Hattie, 2008; Sweeney & Sterman, 2007). As Cunningham (2014) wrote, 'Schools are hard to change: they have enormous inertia and tend to absorb or assimilate new approaches or structures in order to maintain themselves' (p. 72). Shifting school systems takes concerted, collaborative effort. Beabout (2012) argued,

> Collaborative work that examines a school's external environment and internal functions and relates them to that school's purposes *never* happens without effort. It is hard (and thoughtful) work that must be sustained by leadership, supported with time and resources, and can only happen in a climate where risk-taking, support, and collaborative learning exist. (p. 21)

If we want students to learn to think in systems and work with complex systems methods, we must build teacher and school leader capacity to teach and support the teaching of systems literacy knowledge, skills, and dispositions. Through a focused effort on building capacity among school professionals to infuse their work with complex systems core ideas and context relevant methods, systems literacy could serve as a powerful unifying theme and common language for addressing school improvement and for bringing the world of education fully into the 21st century. Byrne (2014) wrote, 'If the complexity frame of reference changes the way we think, and for me it certainly does, then it should also change not only what we teach but also the way we teach' (p. 49). Changing the way educators see the world can be a powerful leverage point for helping them to rethink the curriculum and the ways they support student learning—the development of their systems literacy.

References

Ackoff, R. L. (1997). Systems, messes and interactive planning. *The Societal Engagement of Social Science*, *3*, 417-438.

Alperovitz, G., Speth, J. G., & Guinan, J. (2015). The Next System Project: New political-economic possibilities for the 21st century. Retrieved from http://thenextsystem.org/#updates

Anderson, P.W. (1972). More is different: Broken symmetry and the nature of the hierarchical structure of science. *Science, 177*(4047), 393-396.

Author, C. (2015). The complexity paradigm in education: Skills and dispositions for grappling with complex systems. Proceedings from AERA '15: American Educational Research Association. Chicago, IL.

Author. (2016a). Systems literacy in three dimensions: Cultural, operational, and critical competencies for living in a complex world. (under review).

Author. (2016b). Becoming systems literate. (under review).

Bar-Yam, Y., Ramalingam, C., Burlingame, L., & Ogata, C. (2004). *Making things work: Solving complex problems in a complex world*. Cambridge, MA: NECSI,

Knowledge Press.
Beabout, B.R. (2012). Turbulence, perturbance, and educational change. *Complicity: An International Journal of Complexity and Education, 9*(2), 1-14. Retrieved from http://search.proquest.com/openview/aefd9017d8bd03e973755fad7bdd6e44/1?pq-origsite=gscholar
Betts, F. (1992). How systems thinking applies to education. *Educational Leadership*, *50*(3), 38–41. doi:10.1579/0044-7447
Bryk, A. S., Gomez, L. M., Grunow, A. (2011). Getting ideas into action: Building networked improvement communities in education. Carnegie Foundation for the Advancement of Teaching, Stanford, CA, essay, retrieved from http://www.carnegiefoundation.org/spotlight/webinar-bryk-gomez-building-networkedimprovement-communities-in-education
Burneko, G. (2015). The starry night sky. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 32-48). New York, NY: Routledge.
Byrne, D. (2014). Thoughts on a pedagogy of complexity. *Complicity: An International Journal of Complexity and Education, 11*(2), 40-50. Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/view/22963
Byrne, D. & Callaghan, G. (2014). *Complexity theory and the social sciences: The state of the art.* New York, NY: Routledge.
Capra, F. (1975). *The Tao of physics: An exploration of the parallels between modern physics and eastern mysticism*. Berkeley, CA: Shambhala.
Capra, F., & Luisi, P. L. (2014). *The systems view of life: A unifying vision*. Cambridge: Cambridge University Press.
Cassell, J. A., & Nelson, T. (2010). Visions lost and dreams forgotten: Environmental education, systems thinking, and possible futures in American public schools. *Teacher Education Quarterly*, *37*(4), 179-197. Retrieved from http://go.galegroup.com/ps/i.do?id=GALE%7CA246449260&v=2.1&u=vol_b92b&it=r&p=ITOF&sw=w
Colella, V. S., Klopfer, E., & Resnick, M. (2001). *Adventures in modeling: Exploring complex, dynamic systems with StarLogo*. New York: Teachers College Press.
Combs, A. L. (2015). My life in chaos. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 72-92). New York, NY: Routledge.
Conklin, J. (2009). *Building shared understanding of wicked problems*. Interview with Christensen, K. *Rotman Magazine*, the alumni magazine of Rotman School of Management. Retrieved from http:// www.cognexus.org/Rotman-interview_SharedUnderstanding.pdf
Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Los Angeles, CA: Sage Publications.
Creative Learning Exchange. (2016). About the Creative Learning Exchange. Retrieved from http://www.clexchange.org/cle/about.asp
Creswell, J. W. (2013). Qualitative inquiry and research design: Choosing among five traditions (3rd ed.). Thousand Oaks, CA: Sage Publications.
Cunningham, C. A. (2014). *Systems theory for pragmatic schooling: Toward principles*

of democratic education. New York, NY: Palgrave MacMillan.

Denning, P. J. (2007). Mastering the Mess. *Communication of the ACM*, *50*(4), 21–25. doi:10.1145/1232743.1232763

Dubberly, H. (2014). A systems literacy manifesto. In *Proceedings of RSD3, Third Symposium of Relating Systems Thinking to Design*. Oslo, Norway: Oslo School of Architecture and Design, October 15-17, 2014. Retrieved from http://systemic-design.net/wp-content/uploads/2014/08/Hugh_Dubberly_systems_manifesto.pdf

Eisler, R. (2015). Human possibilities: An integrated systems approach. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 93-113). New York, NY: Routledge.

Fisher, D. M. (2011). "Everybody thinking differently": K–12 is a leverage point. *System Dynamics Review*, *27*(4), 394–411. doi:10.1002/sdr.473

Forrester, J. W. (2007). System dynamics—a personal view of the first fifty years. *System Dynamics Review*, *23*(2-3), 345–358. doi:10.1002/sdr.382

Forrester, J. W. (1969). *Urban Dynamics.* Cambridge, MA: M.I.T. Press.

Freire, P. (1985). Reading the world and reading the word: An interview with Paulo Freire. *Language Arts*, *62*(1), 15–21. Retrieved from http://www.jstor.org/stable/41405241

Gleick, J. (1987). *Chaos: Making a new science*. New York, N.Y., U.S.A: Viking.

Goerner, S. J. (2015). Bringing forth that which is within: How an invisible hand led me to a life that "feels like my own." In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 156-169). New York, NY: Routledge.

Grauwin, S., Beslon, G., Fleury, É., Franceschelli, S., Robardet, C., Rouquier, J.-B., & Jensen, P. (2012). Complex systems science: Dreams of universality, interdisciplinarity reality. *Journal of the American Society for Information Science and Technology*, *63*(7), 1327–1338. doi:10.1002/asi.22644

Green, B. (2012). Subject-specific literacy and school learning: A revised account. In Green, B. & Beavis, C. (Eds.), *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Green, B., & Beavis, C. (2012). *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Hattie, J. (2009). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement*. London: Routledge.

Kauffman, S. A. (1995). *At home in the universe: The search for laws of self-organization and complexity*. New York: Oxford University Press.

Kagan, S. (2010). Cultures of sustainability and the aesthetics of the pattern that connects. *Global Mindset Change*, *42*(10), 1094–1101. doi:10.1016/j.futures.2010.08.009

Kania, J. & Kramer, M. (2013). Embracing emergence: How collective impact addresses complexity. *Stanford Social Innovation Review.* Retrieved from http://ssir.org/articles/entry/embracing_emergence_how_collective_impact_addresses_complexity

Koffka, K. (2013). *Principles of gestalt psychology.* Routledge. Retrieved from https://books.google.com/books?id=tWxHAQAAQBAJ&dq=koffka+other+more&lr=&source=gbs_navlinks_s.

Linden, K.V. (2006). A grounded approach to the study of complex systems. *World Futures, 62*(7), 491-497. doi:10.1080/02604020600912806

Low, A. (2015). Introduction: The complexity of life and lives of complexity. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 1-3). New York, NY: Routledge.

Maani, K. E., & Maharaj, V. (2004). Links between systems thinking and complex decision making. *System Dynamics Review*, *20*(1), 21–48. doi:10.1002/sdr.281

Meadows, D. (1999). Leverage points: Places to intervene in a system. Hartland, VT: The Sustainability Institute.

Meadows, D. H., & Wright, D. (2008). *Thinking in systems: A primer*. White River Junction, VT: Chelsea Green Publishing.

Metz, S. (2012). Systems thinking. *The Science Teacher*, *79*(7), 6. Retrieved from http://go.galegroup.com/ps/i.do?id=GALE%7CA307184829&v=2.1&u=vol_b92b&it=r&p=ITOF&sw=w

Mitchell, M. (2009). *Complexity: A guided tour*. New York, NY: Oxford University Press.

Montuori, A. (2015). Complexity and transdisciplinarity: Reflections on theory and practice. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 170-200). New York, NY: Routledge.

Morgan, G. (2006). *Images of organization.* Thousand Oaks, CA: Sage Publications.

Mowat, F. (1963). *Never cry wolf*. Boston, MA: Little, Brown and Company.

National Council for the Social Studies (NCSS). (2013). The College, Career, and Civic Life (C3) Framework for Social Studies State Standards: Guidance for Enhancing the Rigor of K-12. Silver Spring, MD: NCSS. Retrieved from http://www.socialstudies.org/system/files/c3/C3-Framework-for-Social-Studies.pdf

National Governors Associate for Best Practices. (2010). *Common Core State Standards*. Washington, D.C.: Council of Chief State School Officers. Retrieved from http://www.corestandards.org/

NGSS Lead States. (2013). *Next Generation Science Standards*: For states, by states; Appendix A: Conceptual shifts in the *Next Generation Science Standards*. In *A Framework for K-12 Science Education: Practices, crosscutting concepts, and core ideas*. Washington, DC: Achieve, Inc. Retrieved from http://www.nap.edu/catalog.php?record_id=13165

Ogilvy, J. (2015). Systems theory, arrogant and humble. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 4-16). New York, NY: Routledge.

Olds, L. E. (2015). Systems patterns and possibilities. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 17-31). New York, NY: Routledge.

Patton, M. Q. (2011). *Developmental evaluation: Applying complexity concepts to enhance innovation and use*. New York: Guilford Press.

Plate, R., & Monroe, M. (2014). A structure for assessing systems thinking. *The Creative Learning Exchange*, *23*(1), 1-6. Retrieved from http://www.clexchange.org/ftp/newsletter/CLEx23.1.pdf

Richmond, B. (1993). Systems thinking: critical thinking skills for the 1990s and beyond. *System Dynamics Review*, *9*(2), 113-133. doi:10.1002/sdr.4260090203

Richmond, B., Peterson, S., & High Performance Systems, Inc. (2001). *An introduction to systems thinking: STELLA software*. Lebanon, N.H: High Performance Systems, Inc.

Rogers, M., Pfaff, T., Hamilton, J., & Erkan, A. (2013). Incorporating sustainability and 21st-century problem solving into physics courses. *The Physics Teacher*, *51*(6), 372. doi:10.1119/1.4818380

Sahtouris, E. (2015). A passion for pushing the limits. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 49-71). New York, NY: Routledge.

Senge, P. M. (1990). *The fifth discipline: The art and practice of the learning organization*. New York: Doubleday/Currency.

Senge, P. M. (2000). *Schools that learn: A fifth discipline fieldbook for educators, parents, and everyone who cares about education*. New York: Doubleday.

Senge, P. M. (2012). Creating schools for the future, not the past for all students. *Leader to Leader*, (65), 44–49. doi:10.1002/ltl.20035

Shenton, A. K. (2004). "Strategies for ensuring trustworthiness in qualitative research projects." *Education for Information*, *22,* 63-75. Retrieved from http://search.ebscohost.com.ezproxy.uvm.edu/login.aspx?direct=true&db=aph&AN=13857302&site=ehost-live

Snyder, S. (2013). "The simple, the complicated, and the complex: Educational reform through the lens of complexity theory." *OECD Educational Working Papers,* No. 96, OECD Publishing. doi: 10.1787/5k3txnpt1lnr-en

Stafford, S. G. et al. (2010). Now is the time for action: Transitions and tipping points in complex environmental systems. *Environment: Science and policy for sustainable development, 52*(1), 38-45. doi:10.1080/00139150903481882

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review, 18*(4), 501-531. doi:10.1002/sdr.261

Stillman, S. (2006). Grounded theory and grounded action: Rooted in systems theory. *World Futures, 62*(7), 498-504. doi:10.1080/02604020600912830

Sweeney, L. B. (n.d.). Thinking about systems: 12 habits of mind. Linda Booth Sweeney. Retrieved from http://www.lindaboothsweeney.net/thinking/habits.

Sweeney, L. B. (2014). Learning to connect the dots: Developing children's systems literacy. CLEx23.2.pdf. Spring 2014. 1-12.

Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, *16*(4), 249–286. doi:10.1002/sdr.198

Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review*, *23*(2-3), 285–311. doi:10.1002/sdr.366

Toscano, P.M. (2006). The study of global solutions: A postmodern systems thinking view of grounded theory/grounded action. *World Futures: The Journal of New Paradigm Research, 62*(7), 505-515. doi:10.1080/02604020600912848

Tucker, B. (2011). The dream deferred: How "college and career readiness" looks from below. *English Journal, 100*(3), 115-116. Retrieved from http://search.proquest.com/docview/837350626?accountid=14679

Waters Foundation. (2014). Habits of a systems thinker. Systems Thinking in Schools. Retrieved from http://watersfoundation.org/systems-thinking/habits-of-a-systems-thinker/.

Waters Foundation. (2016). Systems thinking in schools. Retrieved from http://watersfoundation.org/

Wessels, T. (2006). *The myth of progress: Toward a sustainable future.* Burlington, VT.: University of Vermont Press.

Chapter 5: Implications and Conclusion

5.1. Living in a New Age

In 1947, W.H. Auden published *The Age of Anxiety,* a Pulitzer Prize winning poem expressing a sense of apprehension and confusion in an industrialized world recently rocked by war and genocide (Jacobs, 2012). The title is telling. “Anxiety is a type of fear usually associated with the thought of a threat or something going wrong in the future, but can also arise from something happening right now” (Mental Health Foundation, 2015, n.p.). It was a fitting word for an age of such uncertainty. In Auden’s time, the rate of technological advance had risen through the war, and it would only pick up speed going forward. In the decades to come, the effects of human ingenuity would be both miraculous and horrifying. The 20th century gave us nuclear power and nuclear bombs. It gave the common man a car, and it gave the Earth a fever. It generated in America unprecedented wealth and precipitated devastating inequality, levels of the latter as extreme today as they were on the eve of the Great Depression (DeSilver, 2013). Can we be surprised that in the United States today anxiety is the most common mental illness (ADAA, 2016)?

In the time since the Industrial Revolution, we have certainly moved from one historical era into another, but Rockström et al. (2009) claimed that we have also moved from one geological age into another. They referred to the new age as the Anthropocene to emphasize our collective human impact on the physical world. But in their work, they also pointed to a new form of human agency: “For the first time, we are trying to *quantify* [emphasis added] the safe limits outside of which the Earth system cannot continue to function in a stable, Holocene-like state” (p. 474). Their research, utilizing the big data of the 21st century and emphasizing the interdependence of nested complex systems, is firmly rooted in what Ackoff (1997) called the Systems Age. New developments like these hold great potential, but Ackoff argued,

> Neither the hardware nor the software of the Postindustrial Revolution provides panaceas for our problems. They can be used either to create or to solve problems, and they can solve them either well or badly. The net effect of this revolution will depend on how well we use its technology and the ends for which we do so. (p. 426)

We have the technology to solve many of today's most daunting problems. The question is whether we have the collective wisdom or will to use it well. In the time since Auden published that famous poem, this has become increasingly clear: "When human beings evolved, the challenge was survival in a world dominated by systems we could barely influence but that determined how we lived and died. Today the challenges we face are the result of systems we have created" (Sterman, 2002, p. 527).

Humans today have the power to shape the Earth and determine the future. Collectively we exercise that power everyday though rarely with eyes wide open. For the first time in history, we have the scientific and computational capacity to measure our impact on the world, and we have the technological and communication capacity to witness our impact on distant others in real time. We have access to the information we need to grapple with complex realities. Learning to read and interpret the systems around us and learning to write and design new ones is about claiming agency in an Age of Anxiety and moving with eyes wide open into the Age of Complexity.

5.2. Arriving at Complexity

I taught English for twelve years. I enjoyed teaching literature and writing and loved teaching grammar, but I was often disillusioned by how removed the world of school felt from the world around it. I have long been drawn to essayists like Ralph Waldo Emerson who emphasized the interconnectedness of humans to one another and to the natural world, and I struggled with the seeming contradiction between that interdependence and his other focus on self-reliance. That tension and ambiguity drew me into literature. I have also long admired authors like Bill McKibben who connect literary style to scientific ways of knowing through critical, creative nonfiction. It is only in recent years that I have come to understand these personal inclinations as attributes of systems literacy. I did not have the language of complex systems to synthesize those perspectives before the summer of 2008.

Looking for a more resonant way of teaching English to high schoolers, I teamed up with colleagues to develop an interdisciplinary, sustainability-themed curriculum. With a bachelor's and most of a master's degree in English along with a good deal of coursework in education, my own academic background was distinctly lacking in math and science. Because I did not want to teach a soft version of sustainability rooted in personal ideology or my own liberal politics, I knew I had some gaps to fill. I took a summer off of my English studies to enroll in a couple of courses on educating for sustainability at Antioch University of New England. In one of those courses, the professor taught the "principles of sustainability" through the lens of complex systems clearly articulating a series of natural laws that govern not only natural living systems but also complex systems of every type. This perspective provided scientific explanations for general inclinations that had to that point felt merely intuitive to me, explaining, for instance, why the economy as designed *cannot* grow indefinitely, how destroying species and habitats *now* impacts *future possibilities* in ways we will probably never have the capacity to predict (see Wessels, 2006). After that summer, I returned to finish my second degree in English, but from that point on, the scientific concepts of self-organization and emergence would pop out at me from novels and news stories at every turn. I would never see the world in the same way again.

The complex systems theme resonated for me immediately, and in the short few years I taught after that summer course, I saw the potential it had to resonate for students as well. I needed to learn more. I was drawn to the University of Vermont (UVM) because it offered not only a PhD in Educational Leadership and Policy Studies but also a certificate of graduate studies in complex systems. I enrolled intending to earn both. But UVM's approach to complex systems surprised me. I soon learned that the courses required for the certificate were deeply rooted in mathematics and computer science. Sitting in on one, for the first few days of the semester I was able to follow along with much of the theoretical background, and I was excited to see these concepts put to use in what for me was a very new context. In week two, when I saw the first homework assignment (in a graduate level computer science course), I felt completely illiterate. If *this* was "complex systems," what was the "complex systems" theme that had made so much sense to me before?

For a while after that, the more I dug in, the more confused I was about all of the different approaches I encountered. I had known of *systems thinking* and *system dynamics* from my teaching days. What was *complexity theory*, and was it the same as *chaos theory*? How did *evolutionary theory* connect? Or *cybernetics, cellular automata, network analysis, agent-based modeling*? As I explored the concept of complex systems across a wide range of literature, these are the types of terms I encountered. They were clearly all connected, but how? And what did they have to do with that interdisciplinary theme that had so inspired me as a high school English teacher? I wanted one document to pull what I saw as related concepts into a package designed to translate and transmit this broad body of knowledge into the world of education. Ultimately, that is what I produced through the dissertation process.

In the time I have worked on this study, a few important resources have been published, texts that would have been helpful to me early on. Capra and Luisi's (2014) *A Systems View of Life* collected many of these branches of complexity into a single textbook, nesting them within the historical, scientific, mathematical, and cultural contexts that demonstrate how many distinct innovations together constitute a new paradigm. Cunningham's (2014) *Systems Theory for Pragmatic Schooling* articulated clearly how this new paradigm connects to education, and Mantuori's (2015) edited collection of essays *Journeys in Complexity* told several stories of how individuals made their way into and make their way in the world of complex systems. Together, these texts and others have provided me with much of what I was looking for when I started this degree back in 2012. Had I encountered these then, I probably would not have built a definition of systems literacy or a grounded theory of how one becomes systems literate. And yet, though the literature of complexity is clearly taking off, I believe what I have managed to produce here constitutes a unique and useful contribution.

5.3. Findings in Brief

5.3.1. Systems literacy—a working definition. After four years of actively studying complexity, I would still feel illiterate in a graduate level computer science or mathematics course, but there are plenty of things that computer and math professors may not know about educating youth in the 21st century or analyzing the ambiguity of the human experience as expressed through literature. My definition of systems literacy does not diminish the necessity of domain specific expertise in computers, math, science, social sciences, literature, or cultural studies. Rather, it assumes that that expertise will be developed through disciplinary studies and experience, and it focuses instead on the common threads of complexity that connect and transcend the disciplines. Reviewing the findings briefly, individuals who are culturally literate in complex systems

- **know the context and language of complex systems** stemming from at least one branch of complexity studies (e.g., complexity theories, systems thinking/system dynamics, complex systems computational methods, etc.);
- **read the world through a systems lens**, actively employing systems thinking and/or a complexity frame of reference to see connections between parts and wholes, between diverse subjects and ideas, and between common patterns across contexts;
- and **comprehend self-organization and emergence**, understanding how nestedness, interdependence, and scale impact adaptation, evolution, and emergent properties.

Individuals who are operationally literate in complex systems

- **cross disciplinary boundaries**, using knowledge about systems to enhance domain specific knowledge and skills (e.g., knowledge and skills in math, computing, data analysis, design, policy work, etc.), and vice versa;
- **employ scientific inquiry and empirical methods** to understand reality, emphasizing both structure and agency, remaining open to new and contradictory information, and embracing ambiguity and uncertainty;
- **work to understand nonlinear change**, looking beyond simple cause-effect relationships to identify underlying variables and patterns of change over time, anticipate unintended consequences, identify points of leverage, and design effective solutions;
- and **activate multiple modes of communication** (which may include the creation of computer simulations, graphic illustrations, written descriptions, etc.) throughout the learning process to structure thinking and construct and share knowledge and understanding.

Finally, those who are critically literate

- **pursue multiple perspectives** in a given situation to avoid polarized or dichotomous thinking and increase personal and collective understanding;
- **recognize the power of mental models** and challenge assumptions and heuristics that limit one's ability to align understanding with empirical evidence;
- and **engage in active, adaptive learning** to develop skills required for new situations and to make meaning out of new information.

Educators from the systems thinking and system dynamics traditions have come to similar conclusions before. Sterman's (2002) words resonate particularly well with these findings and the implications for education I have discussed in preceding chapters:

> What prevents us from overcoming policy resistance is not a lack of resources, technical knowledge, or a genuine commitment to change. What thwarts us is our lack of a meaningful systems thinking capability. That capability requires, but is much more than, the ability to understand complexity, to understand stocks and flows, feedback, and time delays. It requires, but is much more than, the use of formal models and simulations. It requires an unswerving commitment to the highest standards, the rigorous application of the scientific method, and the inquiry skills we need to expose our hidden assumptions and biases. It requires that we listen with respect and empathy to others. It requires the curiosity to keep asking those 'why' questions. It requires the humility we need to learn and the courage we need to lead, though all our maps are wrong. That is the real purpose of system dynamics: To create the future we truly desire—not just in the here and now, but globally and for the long term. Not just for us, but for our children. Not just for our children, but for all children. (p. 527)

The findings of my grounded theory study connect Sterman's ideas from the domain of system dynamics to a larger context of education for complexity writ large. I offer this definition not as a fixed entity but as a contribution to an evolving conversation. I hope it will receive enough attention to be implemented and adapted by others moving forward.

5.3.2. Becoming systems literate—a theory in progress. Similarly, in answering how one becomes systems literate, I have presented a grounded theory that is by design a work in progress (Corbin & Strauss, 2008). I have found that in becoming systems literate, individuals experience overlapping cycles of grounding, questioning, broadening, integrating, and developing a systems lens. Grounding may include

- grounding in natural and manmade systems, including communities and social systems, but especially agricultural or food systems;
- grounding in real-world problems;
- and grounding in one or more disciplines.

Questioning may include

- asking big questions (and exploring 'and/also' rather than 'either/or' answers);
- questioning methodologies, ontologies, mental models, and personal biases;
- questioning established structures to explore better solutions;
- and embracing ambiguity and uncertainty.

Broadening may include

- broadening through formal education;
- broadening through independent or collaborative learning;
- and broadening through non-academic experiences.

Integrating may include

- integrating knowledge across fields and experiences;
- integrating academic and intuitive knowledge (through tension);
- integrating through narrative forms;
- and learning, integrating, adapting, evolving.

Finally, developing a systems lens may include

- learning the culture (language, literature, history) of complexity;

- developing a systems lens through formal and informal education;
- and refining that lens through modeling and experimentation.

This theory is multi-dimensional, incorporating common themes and variations in an intentionally open-ended structure. Its implications do not point toward a single way to rethink education to prepare systems literate individuals. Rather, they offer myriad opportunities to dig into such work.

5.4. Implications—Intervening at Points of High Leverage

I have been intentional in stating that my findings should be adapted and revised going forward and that they should be interpreted differently for different educational contexts. These stances resonate both with the grounded theory methodological approach to generating knowledge in the context of complexity and to systems theories of organizational change. Corbin and Strauss (2008) wrote that grounded theory is well suited to rigorous study in "a world that is complex, often ambiguous, evincing change as well as periods of permanence; where action itself although routine today may be problematic tomorrow; where answers become questionable and questions ultimately produce answers" (p. 6). They argued, in the Pragmatic tradition, that their methods were based on two key assumptions:

> One is that truth is equivalent to 'for the time being this is what we know—but eventually it may be judged partly or even wholly wrong.' Another assumption is that despite that qualification, the accumulation of knowledge is no mirage. (p. 4)

I have grounded my definition of systems literacy and my theory of how one becomes literate in data from online resources, published texts, and conversations with complexity scholars and systems educators and have presented my findings to be useful for teachers and school leaders now, understanding that in an age of rapid change, the definition and theory will both have to evolve to remain relevant.

This dissertation does not promote specific education practices, but instead attempts to intervene in school change at what Meadows (1999) identified as higher points of leverage: "the goals of the system"; "the mindset or paradigm out of which the system—its goals, structure, rules, delays, parameters—arises"; and, especially in my third journal article, I focused on "the power to add, change, evolve or self-organize system structure" (p. 3). I agree with Cunningham (2014) who wrote, "Rather than looking to systems theory for *techniques* to improve schools, . . . we should use it to reframe the *meaning* and purpose of schooling, to reconstruct the effects that schooling has on our students" (p. 122). I agree with Marshall (2006) who wrote, "Change in internal meaning, not change by external mandate, is the source and catalyst for living system transformation" (p. 35). And I agree with Beabout (2012), who wrote, "If schools are to develop as learning organizations, then change will always require individuals to come together and re-examine the goals of their school and how current practices serve to meet them" (p. 26). Authors like these have inspired and informed this study.

My work on systems literacy has been an exercise in connecting conversations across disparate contexts. The various branches of complexity studies are cultures unto themselves, and I do not mean to obscure the distinct traditions by overemphasizing commonalities. However, in important ways these cultures share some of their vocabulary, many of their metaphors, and a common understanding of interdependence that is so desperately needed on a small planet in trying times. Complexity is a transcendent, unifying theme. It offers a language to connect academic disciplines and traditions as well as scientific and intuitive ways of knowing. It is rooted in the complementary skills of analysis and synthesis that illuminate both the structures of the systems around us and our agency to act within them. It makes clear the myriad ways we are all connected to one another and to the world on which we depend. Systems literacy offers access to the hopeful Age of Complexity.

6. Comprehensive Bibliography

ADAA. (2016). Facts and statistics. Anxiety and Depression Association of America. Retrieved from http://www.adaa.org/about-adaa/press-room/facts-statistics

Ackoff, R. L. (1997). Systems, messes and interactive planning. *The Societal Engagement of Social Science*, *3*, 417-438.

Alperovitz, G., Speth, J. G., & Guinan, J. (2015). The Next System Project: New political-economic possibilities for the 21st century. Retrieved from http://thenextsystem.org/#updates

Anderson, P.W. (1972). More is different: Broken symmetry and the nature of the hierarchical structure of science. *Science, 177*(4047), 393-396.

Anyon, J. (1980). Social class and the hidden curriculum of work. *The Journal of Education, 162*(1), 67-92. Retrieved from http://www.jstor.org/stable/42741976

Apple, M. W. (2008). Can schooling contribute to a more just society? *Education, Citizenship and Social Justice, (3)*3, 239-261. Web. 4 Dec. 2014. doi:10.1177/1746197908095134

Auden, W.H. (2011). *The Age of Anxiety: A Baroque Eclogue.* A. Jacobs (Ed.). Princeton, NJ: Princeton University Press.

Banathy, B. H. (1991). *Systems Design of Education: A Journey to Create the Future*. Educational Technology.

Banathy, B.H., & Rowland, G. (2004). *Guiding Our Evolution: If we don't do it, who will?* Retrieved from http://documents.mx/documents/guiding-our-evolution-if-we-dont-do-it-who-will.html

Bar-Yam, Y., Ramalingam, C., Burlingame, L., & Ogata, C. (2004). *Making things work:*

Solving complex problems in a complex world. Cambridge, MA: NECSI, Knowledge Press.

Beabout, B.R. (2012). Turbulence, perturbance, and educational change. *Complicity: An International Journal of Complexity and Education, 9*(2), 1-14. Retrieved from http://search.proquest.com/openview/aefd9017d8bd03e973755fad7bdd6e44/1?pq-origsite=gscholar

Bennett, L. & Sweeney, L. B. (n.d.). If you cut a cow in half, do you get two cows? Center for Ecoliteracy. Retrieved February 19, 2015, from http://www.ecoliteracy.org/essays/if-you-cut-cow-half-do-you-get-two-cows

Betts, F. (1992). How systems thinking applies to education. *Educational Leadership*, *50*(3), 38–41. doi:10.1579/0044-7447

Bryk, A. S., Gomez, L. M., Grunow, A. (2011). Getting ideas into action: Building networked improvement communities in education. Carnegie Foundation for the Advancement of Teaching, Stanford, CA, essay, retrieved from http://www.carnegiefoundation.org/spotlight/webinar-bryk-gomez-building-networkedimprovement-communities-in-education

Burneko, G. (2015). The starry night sky. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 32-48). New York, NY: Routledge.

Byrne, D. (2014). Thoughts on a pedagogy of complexity. *Complicity: An International Journal of Complexity and Education, 11*(2), 40-50. Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/view/22963

Byrne, D. & Callaghan, G. (2014). *Complexity theory and the social sciences: The state* *of the art.* New York, NY: Routledge.

Cabrera, D., & Cabrera, L. (2015). *Systems thinking made simple: New hope for solving wicked problems*. [place of publication not indicated]: Odyssean.

Capra, F. (1975). *The Tao of physics: An exploration of the parallels between modern physics and eastern mysticism*. Berkeley, CA: Shambhala.

Capra, F., & Luisi, P. L. (2014). *The systems view of life: A unifying vision*. Cambridge, MA: Cambridge University Press.

Cassell, J. A., & Nelson, T. (2010). Visions lost and dreams forgotten: Environmental education, systems thinking, and possible futures in American public schools. *Teacher Education Quarterly*, *37*(4), 179-197. Retrieved from http://go.galegroup.com/ps/i.do?id=GALE%7CA246449260&v=2.1&u=vol_b92b&it=r&p=ITOF&sw=w

Charmaz, K. (2000). Grounded theory: Objectivist and constructivist methods. In N.K. Denzin & Y.S. Lincoln (Eds.), *Handbook of qualitative research* (p. 509-535). Thousand Oaks, CA: Sage Publications.

Cilliers, P. (1998). *Complexity and postmodernism: Understanding complex systems*. London: Routledge.

Cloud, J. P. (2010). Educating for a sustainable future. In H. H. Jacobs (Ed.), *Curriculum 21: Essential education for a changing world*. Alexandria, VA: Association for Supervision and Curriculum Development.

Cloud, J. P., ed. (2012). Education for sustainability: EfS standards and performance indicators. The Cloud Institute for Sustainability Education. Retrieved from http://cloudinstitute.org/cloud-efs-standards/

Colella, V. S., Klopfer, E., & Resnick, M. (2001). *Adventures in modeling: Exploring complex, dynamic systems with StarLogo*. New York: Teachers College Press.

Combs, A. L. (2015). My life in chaos. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 72-92). New York, NY: Routledge.

Conklin, J. (2009). *Building shared understanding of wicked problems*. Interview with Christensen, K. *Rotman Magazine*. Retrieved from http:// www.cognexus.org/Rotman-interview_SharedUnderstanding.pdf

Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Los Angeles, CA: Sage Publications.

Creswell, J. W. (2013). Qualitative inquiry and research design: Choosing among five traditions (3rd ed.). Thousand Oaks, CA: Sage Publications.

Creative Learning Exchange. (2016). About the Creative Learning Exchange. Retrieved from http://www.clexchange.org/cle/about.asp

Cunningham, C. A. (2014). *Systems theory for pragmatic schooling: Toward principles of democratic education.* New York, NY: Palgrave MacMillan.

Denning, P. J. (2007). Mastering the Mess. *Commun. ACM*, *50*(4), 21–25. doi:10.1145/1232743.1232763

Denzin, N. K., & Lincoln, Y. S. (2000). *Handbook of qualitative research*. Thousand Oaks, CA: Sage Publications.

DeSilver, D. (2013). U.S. income inequality, on rise for decades, is now highest since 1928. Pew Research Center. Retrieved from http://www.pewresearch.org/facttank/2013/12/05/u-s-income-inequality-on-rise-for-decades-is-now-highest-since-1928/

Dias, S. (2015). Imagination and complexity: Creative-adaptive capacity for teaching and learning in the 21st century. Proceedings from AERA '15: American Educational Research Association. Chicago, IL.

Doll, W. E. (1989). Complexity in the classroom. *Educational Leadership*, *47*(1), 65-70.

Dubberly, H. (2014). A systems literacy manifesto. In *Proceedings of RSD3, Third Symposium of Relating Systems Thinking to Design*. Oslo, Norway: Oslo School of Architecture and Design, October 15-17, 2014. Retrieved from http://systemic-design.net/wp-content/uploads/2014/08/Hugh_Dubberly_systems_manifesto.pdf

Edelstein, W. (2011). Education for democracy: Reasons and strategies. *European Journal of Education*, *46*(1), 127–137. doi:10.1111/j.1465-3435.2010.01463.x

Eisler, R. (2015). Human possibilities: An integrated systems approach. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 93-113). New York, NY: Routledge.

Faulkner, J., Ocean, J., & Jordan, K. (2012). Designing multiliteracies in 3D. In Green, B. & Beavis, C. (Eds.), *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Fisher, D. M. (2011). "Everybody thinking differently": K–12 is a leverage point. *System Dynamics Review*, *27*(4), 394–411. doi:10.1002/sdr.473

Forrester, J. W. (1969). *Urban Dynamics.* Cambridge, MA: M.I.T. Press.

Forrester, J. W. (2007). System dynamics—a personal view of the first fifty years. *System Dynamics Review*, *23*(2-3), 345–358. doi:10.1002/sdr.382

Forrester, J. W. (2009). Learning through system dynamics as preparation for the 21st century. Sloan School of Management. Massachusetts Institute of Technology. Retrieved from http://www.clexchange.org/curriculum/complexsystems/complexsystems_resources.asp

Freire, P. (1985). Reading the world and reading the word: An interview with Paulo Freire. *Language Arts*, *62*(1), 15–21. Retrieved from http://www.jstor.org/stable/41405241

Freire, P. (2000). *Pedagogy of the oppressed*. New York, NY: Continuum.

Friedman, M. (2002). *Capitalism and freedom*. Chicago, IL: The University of Chicago Press.

Geert, P. V., & Steenbeek, H. (2014). The good, the bad and the ugly? The dynamic interplay between educational practice, policy and research. *Complicity: An International Journal of Complexity and Education*, *11*(2). Retrieved from http://ejournals.library.ualberta.ca/index.php/complicity/article/view/22962

Gleick, J. (1987). *Chaos: Making a new science*. New York, N.Y., U.S.A: Viking.

Goerner, S. J. (2015). Bringing forth that which is within: How an invisible hand led me to a life that "feels like my own." In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 156-169). New York, NY: Routledge.

Grauwin, S., Beslon, G., Fleury, É., Franceschelli, S., Robardet, C., Rouquier, J.-B., & Jensen, P. (2012). Complex systems science: Dreams of universality, interdisciplinarity reality. *Journal of the American Society for Information*

Science and Technology, *63*(7), 1327–1338. doi:10.1002/asi.22644

Green, B. (2012). Subject-specific literacy and school learning: A revised account. In Green, B. & Beavis, C. (Eds.), *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Green, B., & Beavis, C. (2012). *Literacy in 3D: An integrated perspective in theory and practice*. Camberwell, Victoria, Australia: ACER Press.

Hattie, J. (2009). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement*. London: Routledge.

Jacobs, A. (2012). Introduction. *The Age of Anxiety: A Baroque Eclogue.* W.H. Auden (Author.). Princeton, NJ: Princeton University Press.

Jacobs, H. H., & Association for Supervision and Curriculum Development. (2010). *Curriculum 21: Essential education for a changing world*. Alexandria, VA: Association for Supervision and Curriculum Development.

Kagan, S. (2010). Cultures of sustainability and the aesthetics of the pattern that connects. *Global Mindset Change*, *42*(10), 1094–1101. doi:10.1016/j.futures.2010.08.009

Kania, J. & Kramer, M. (2013). Embracing emergence: How collective impact addresses complexity. *Stanford Social Innovation Review.* Retrieved from http://ssir.org/articles/entry/embracing_emergence_how_collective_impact_addresses_complexity

Kauffman, S. A. (1995). *At home in the universe: The search for laws of self-organization and complexity*. New York: Oxford University Press.

Koffka, K. (2013). *Principles of gestalt psychology.* Routledge. Retrieved from https://books.google.com/books?id=tWxHAQAAQBAJ&dq=koffka+other+more&lr=&source=gbs_navlinks_s.

Kolb, D. A., Boyatzis, R.E., & Mainemelis, C. (2000). Experiential learning theory: Previous research and new directions. In Sternberg, R. J., & Zhang, L. (Eds.), *Perspectives on thinking, learning, and cognitive styles* (227-247). Mahwah, N.J: Lawrence Erlbaum Associates.

Linden, K.V. (2006). A grounded approach to the study of complex systems. *World Futures, 62*(7), 491-497. doi:10.1080/02604020600912806

Lockhart, P. (2008). A mathematician's lament. *Devlin's Angle.* Retrieved from http://www.maa.org/devlin/LockhartsLament.pdf

Low, A. (2015). Introduction: The complexity of life and lives of complexity. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 1-3). New York, NY: Routledge.

Maani, K. E., & Maharaj, V. (2004). Links between systems thinking and complex decision making. *System Dynamics Review*, *20*(1), 21–48. doi:10.1002/sdr.281

Manson, S. M. (2001). Simplifying complexity: a review of complexity theory. *Geoforum*, *32*(3), 405–414. doi:10.1016/S0016-7185(00)00035-X

Marshall, S. P. (2006). *The power to transform: Leadership that brings learning and schooling to life*. San Francisco, CA: Jossey-Bass.

Meadows, D. (1999). Leverage points: Places to intervene in a system. Hartland, VT: The Sustainability Institute.

Meadows, D. H., & Wright, D. (2008). *Thinking in systems: A primer*. White River

Junction, VT: Chelsea Green Publishing.

Mental Health Foundation. (2015). Mental health statistics: Anxiety. Retrieved from https://www.mentalhealth.org.uk/statistics/mental-health-statistics-anxiety

Metz, S. (2012). Systems thinking. *The Science Teacher*, *79*(7), 6. Retrieved from http://go.galegroup.com/ps/i.do?id=GALE%7CA307184829&v=2.1&u=vol_b92b&it=r&p=ITOF&sw=w

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Thousand Oaks, CA: Sage Publications.

Mitchell, M. (2009). *Complexity: A guided tour*. New York, NY: Oxford University Press.

Montuori, A. (2015). Complexity and transdisciplinarity: Reflections on theory and practice. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 170-200). New York, NY: Routledge.

Morgan, G. (2006). *Images of organization.* Thousand Oaks, CA: Sage Publications.

Mowat, F. (1963). *Never cry wolf*. Boston, MA: Little, Brown and Company.

National Council for the Social Studies (NCSS). (2013). The College, Career, and Civic Life (C3) Framework for Social Studies State Standards: Guidance for Enhancing the Rigor of K-12. Silver Spring, MD: NCSS. Retrieved from http://www.socialstudies.org/system/files/c3/C3-Framework-for-Social-Studies.pdf

National Governors Associate for Best Practices. (2010). *Common Core State Standards*. Washington, D.C.: Council of Chief State School Officers. Retrieved from http://www.corestandards.org/

NGSS Lead States. (2013). *Next Generation Science Standards*: For states, by states; Appendix A: Conceptual shifts in the *Next Generation Science Standards*. In *A Framework for K-12 Science Education: Practices, crosscutting concepts, and core ideas*. Washington, DC: Achieve, Inc. Retrieved from http://www.nap.edu/catalog.php?record_id=13165

Nijs, D.E.L.W. (2015). Introduction: Coping with growing complexity in society. *World Futures, 71*(1-2), 1-7. doi: 10.1080/02604027.2015.1087223

O'Day, J. A. (2002). "Complexity, accountability, and school improvement." *Harvard Educational Review 72*(3) 293-329. Retrieved from http://search.proquest.com.ezproxy.uvm.edu/docview/212262583?accountid=146 79

Ogilvy, J. (2015). Systems theory, arrogant and humble. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 4-16). New York, NY: Routledge.

Olds, L. E. (2015). Systems patterns and possibilities. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 17-31). New York, NY: Routledge.

Patton, M. Q. (2002). *Qualitative research and evaluation methods*. Thousand Oaks, CA: Sage Publications.

Patton, M. Q. (2011). *Developmental evaluation: Applying complexity concepts to enhance innovation and use*. New York: Guilford Press.

Plate, R. R. (2006). *Assessing the effectiveness of systems-oriented instruction for preparing students to understand complexity.* (Doctoral dissertation). The University of Florida. Retrieved from http://www.clexchange.org/resources/research.asp

Plate, R., & Monroe, M. (2014). A structure for assessing systems thinking. *The Creative Learning Exchange*, *23*(1), 1-6. Retrieved from http://www.clexchange.org/ftp/newsletter/CLEx23.1.pdf

Poppick, L. (2011). Sea ice-albedo: Earth's chilling reflection. Main Climate News. Retrieved from http://umaine.edu/maineclimatenews/blog/2011/07/06/loops-of-change-the-positive-feedback-loops-that-drive-climate-change-part-i/

Project GUTS. Welcome to Project GUTS. Retrieved from http://www.projectguts.org/

Richmond, B. (1993). Systems thinking: critical thinking skills for the 1990s and beyond. *System Dynamics Review*, *9*(2), 113-133. doi:10.1002/sdr.4260090203

Richmond, B., Peterson, S., & High Performance Systems, Inc. (2001). *An introduction to systems thinking: STELLA software*. Lebanon, N.H: High Performance Systems, Inc.

Robinson, K. (2010, October 14). RSA animate: Changing education paradigms. TED.com. Retrieved from https://www.ted.com/talks/ken_robinson_changing_education_paradigms

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. doi:10.1038/461472a

Rogers, M., Pfaff, T., Hamilton, J., & Erkan, A. (2013). Incorporating sustainability and 21st-century problem solving into physics courses. *The Physics Teacher*, *51*(6), 372. doi:10.1119/1.4818380

Sahtouris, E. (2015). A passion for pushing the limits. In A. Montuori (Ed.), *Journeys in complexity: Autobiographical accounts by leading systems and complexity thinkers* (pp. 49-71). New York, NY: Routledge.

Santa Fe Institute. (2016). Project GUTS: Growing up thinking scientifically. Retrieved from http://santafe.edu/education/k12-project-guts/

Shelburne Farms' Sustainable Schools Project. (2011). The guide to education for sustainability. Shelburne, VT: Shelburne Farms.

Senge, P. M. (1990). *The fifth discipline: The art and practice of the learning organization*. New York: Doubleday/Currency.

Senge, P. M. (2000). *Schools that learn: A fifth discipline fieldbook for educators, parents, and everyone who cares about education*. New York: Doubleday.

Senge, P. M. (2008). *The necessary revolution: How individuals and organizations are working together to create a sustainable world*. New York, NY: Doubleday.

Senge, P. M. (2012). Creating schools for the future, not the past for all students. *Leader to Leader*, (65), 44–49. doi:10.1002/ltl.20035

Shenton, A. K. (2004). "Strategies for ensuring trustworthiness in qualitative research projects." *Education for Information*, *22.* 63-75. Retrieved from http://search.ebscohost.com.ezproxy.uvm.edu/login.aspx?direct=true&db=aph&AN=13857302&site=ehost-live

Snyder, S. (2013). “The simple, the complicated, and the complex: Educational reform through the lens of complexity theory.” *OECD Educational Working Papers,* No. 96, OECD Publishing. doi: 10.1787/5k3txnpt1lnr-en

Stafford, S. G. et al. (2010). Now is the time for action: Transitions and tipping points in complex environmental systems. *Environment: Science and policy for sustainable development, 52*(1), 38-45. doi:10.1080/00139150903481882

Steele, C. (2015). The complexity paradigm in education: Skills and dispositions for grappling with complex systems. Proceedings from AERA ’15: American Educational Research Association. Chicago, IL.

Sterman, J. D. (2002). All models are wrong: Reflections on becoming a systems scientist. *System Dynamics Review, 18*(4), 501-531. doi:10.1002/sdr.261

Stillman, S. (2006). Grounded theory and grounded action: Rooted in systems theory. *World Futures, 62*(7), 498-504. doi:10.1080/02604020600912830

Strauss, A. L., & Corbin, J. M. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory*. Thousand Oaks, CA: Sage Publications.

Sung, N. S., Gordon, J. I., Rose, G. D., Getzoff, E. D., Kron, S. J., Mumford, D., … Kopell, N. J. (2003). Educating future scientists. *Science*, *301*(5639), 1485. doi:10.2307/3835062

Sweeney, L. B. (n.d.). Thinking about systems: 12 habits of mind. Linda Booth Sweeney. Retrieved from http://www.lindaboothsweeney.net/thinking/habits.

Sweeney, L. B. (2009). Systems teaching and farm-based education. Reprinted in Farm Based Education Network. (n.d.). Retrieved February 19, 2015, from http://www.farmbasededucation.org/page/systems-teaching-and-farmbased

Sweeney, L. B. (2014). Learning to connect the dots: Developing children's systems literacy. CLEx23.2.pdf. Spring 2014. 1-12.

Sweeney, L. B., & Meadows, D. (2010). *The systems thinking playbook: Exercises to stretch and build learning and systems thinking capabilities*. White River Junction, VT: Chelsea Green Pub.

Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: Initial results of a systems thinking inventory. *System Dynamics Review*, *16*(4), 249–286. doi:10.1002/sdr.198

Sweeney, L. B., & Sterman, J. D. (2007). Thinking about systems: Student and teacher conceptions of natural and social systems. *System Dynamics Review*, *23*(2-3), 285–311. doi:10.1002/sdr.366

Toscano, P. M. (2006). The study of global solutions: A postmodern systems thinking view of grounded theory/grounded action. *World Futures: The Journal of New Paradigm Research, 62*(7), 505-515. doi:10.1080/02604020600912848

Tucker, B. (2011). The dream deferred: How "college and career readiness" looks from below. *English Journal, 100*(3), 115-116. Retrieved from http://search.proquest.com/docview/837350626?accountid=14679

Umphrey, S. (2002). *Complexity and analysis*. Lanham, MD: Lexington Books.

Vermont Agency of Education (2014). Introduction to the education quality standards. Retrieved from http://education.vermont.gov/documents/EDU-

EQS_Intoduction.pdf

Vermont Board of Education. (2014). Education quality standards (State Board Rule 2000, adopted April 5, 2014). Retrieved from http://education.vermont.gov/state-board/rules/2000

Wagner, T. (2008). *The global achievement gap: Why even our best schools don't teach the new survival skills our children need--and what we can do about it*. New York, NY: Basic Books.

Waters Foundation. (n.d.). The impact of the Systems Thinking in Schools Project: 20 years of research, development and dissemination. Retrieved from http://watersfoundation.org/wp-content/uploads/2012/09/STIS_Research.pdf

Waters Foundation. (2014). Habits of a systems thinker. Systems Thinking in Schools. Retrieved from http://watersfoundation.org/systems-thinking/habits-of-a-systems-thinker/.

Waters Foundation. (2016). Systems thinking in schools. Retrieved from http://watersfoundation.org/

Weil, Zoe. (2012, July 2). Solutionaries: Zoe Weil at TEDxConejo. Retrieved from http://humaneeducation.org/blog/2012/07/02/solutionaries-zoe-weils-new-tedx-talk/

Wessels, T. (2006). *The myth of progress: Toward a sustainable future.* Burlington, VT: University of Vermont Press.

7. Appendices

7.1. IRB Forms

Four documents were submitted to the Institutional Review Board after approval from the dissertation committee. They included a longer version of the interview protocol presented in Appendix 7.4 and the three additional documents identified in the table below and submitted to the dissertation committee separately.

Table 7.1.

IRB Documents

Document Name	Description
IRB Exempt Application – CS 5.22.15	Application protocol for exempt status.
Exemption Certification	Certificate of exemption provided by the Institutional Review Board for this study.
Verbal Consent – CS 5.22.15	Verbal consent form, updated from a previous form for phase two, provided to all new interviewees in phase three of this study.

7.2. Systems Skills Inventory

The eighteen individuals who participated in phases one and two of this study were provided with this survey instrument. Seventeen returned it.

Thank you for taking the time to talk with me about your work with complex systems and the educational path that has led you there. I appreciate your insights and look forward to reviewing this conversation as I continue my research.

A single conversation can cover only so much, and so I have attempted to use our interview to capture information that is unique to you and your own experiences with complex systems. Additionally, though, I am interested in testing a series of ideas that have emerged from earlier conversations like this one. I am curious which of the statements below are relatively unique and which may represent larger patterns within the community of complexity scholars.

Please take the time to respond to each of the statements in the systems skills inventory below. Marginal remarks are welcome.

Again, thank you so much for taking the time to share your ideas and insights with me. You can return this survey in the envelope provided. If the envelope is missing, please send it to me at *Caitlin Steele* . . .

SYSTEMS SKILLS INVENTORY

1. I am fascinated by science in general.				
☐ Strongly disagree	☐ Disagree	☐ Neither agree nor disagree	☐ Agree	☐ Strongly agree
2. I am interested in the intersections between science and society.				
☐ Strongly disagree	☐ Disagree	☐ Neither agree nor disagree	☐ Agree	☐ Strongly agree
3. The scientific method is important to my work with complex systems.				
☐ Strongly disagree	☐ Disagree	☐ Neither agree nor disagree	☐ Agree	☐ Strongly agree
4. I consider myself a scientist.				
☐ Strongly disagree	☐ Disagree	☐ Neither agree nor disagree	☐ Agree	☐ Strongly agree

5. Mathematics is important to my work with complex systems.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

6. I have a strong mathematical background.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

7. I have strong computational skills

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

8. I understand math conceptually.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

9. In my complex systems work, collaborating with one or more colleagues whose skills complement my own allows me to tackle problems that I could not solve alone.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

10. Computers are central to my work with complex systems.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

11. I use computer models to explore questions of complexity.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

12. I use off-the-shelf modeling programs to build models of complex systems.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

13. I write computer code to build models of complex systems.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

14. I consider myself a specialist in one or more academic fields.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

15. I consider myself a generalist across a range of academic fields.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

16. I see connections across traditional academic fields.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

17. Making connections across academic fields is important to my work with complex systems.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

18. In my complex systems work, I collaborate frequently with colleagues within my discipline.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

19. In my complex systems work, I collaborate frequently with colleagues across academic fields.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

20. In my complex systems work, I collaborate with others outside the world of academia.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

21. Collaboration is essential to my work with complex systems.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

22. My complex systems work involves real-world problem solving.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

23. I learned important systems skills and dispositions in my early education (K-12).

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

24. In my early education (K-12), I learned content knowledge that has informed my complex systems work.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

25. I learned important systems skills and dispositions in my undergraduate education.

☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

26. In my undergraduate education, I learned content knowledge that has informed my complex systems work. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
27. I learned important systems skills and dispositions in my graduate education. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
28. In my graduate education, I learned content knowledge that has informed my complex systems work. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
29. I have learned about complex systems collaboratively with peers. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
30. I have learned about complex systems through independent reading. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
31. I have learned about complex systems through attending lectures and/or workshops. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
33. My complex systems skills and dispositions are largely self-taught. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree
33. My content knowledge is largely self-taught. ☐ Strongly disagree ☐ Disagree ☐ Neither agree nor disagree ☐ Agree ☐ Strongly agree

33. Are there specific skills or dispositions required for working with complex systems that are not addressed in the statements above?

34. If your complex systems understandings are heavily informed by the sciences, how would you rank the following branches of science (1 = <u>most</u> important to my understanding of complexity)

____ Not applicable	____ Physics	____ Environmental Science
____ Biology	____ Ecology	____ Other _______________
____ Chemistry	____ Engineering	____ Other _______________

35. Is there a particular book (fiction or nonfiction) that made a strong impact on you early in your exploration of systems thinking and/or complex systems concepts?

36. Was there a particular incident (environmental, economic, etc.) that first led you to grapple with systems approaches to solving problems? If so, what was that incident, and why do you think it resonated with you?

7.3. Phase Two—Interview Protocol

The primary instrument for data collection in phase two of this study took the form of a semi-structured interview with each study participant. Through the questions below, I attempted to outline the types of information that I hoped to collect. Rather than follow this list as a script, I used it as a reference to guide and/or redirect conversations while maintaining space for each of those conversations to take on a life of its own, to open up new lines of inquiry that I may not have captured below.

Table 7.2.

Phase Two Interview Protocol

Interview Protocol
1. Why are you interested in complex systems? 2. Tell me about the educational path that brought you to this current interest. 3. Do you remember when you were first formally introduced to the concept of complex systems? What was the context? What impact did that new way of looking at systems have on you? 4. How would you describe your early education (K-16)? What elements of that education have served you well in your complex systems work? What aspects were less effective or even counter-productive? 5. What skills, dispositions, and knowledge did you need to develop along the way in order to do the work you do now with complex systems? 6. What would you say motivates or drives your work with complex systems? 7. What personal and professional goals do you have for your complex systems work? 8. Why teach systems skills? In what ways might systems skills and dispositions be helpful to today's students? 9. If an early education (K-12) were designed to prepare students to grapple with complexity, what would that education look like?

7.4. Phase Three—Interview Protocol

Semi-structured interviews were an important source of new data collected in phase three of this study. Interviews served two purposes: (1) member-checking my definition of systems literacy and (2) digging more deeply into the question of how one becomes systems literate. I designed the original protocol with a third purpose in mind: (3) exploring ideas for introducing complexity concepts to educators. However, though interviews across all three phases of this study did provide me with several ideas aligned with this third purpose, I did not systematically ask related questions in my phase three interviews. Through the questions presented in Table 7.3 below, I outlined each purpose in terms of the types of information that I planned to collect. Instead of following any of these lists as a script, I used them as references to guide and/or redirect conversations, maintaining space for each conversation to be relatively open-ended. Additionally, I revisited several participants from earlier phases of the study to member-check both my definition of systems literacy and my emerging themes around how one becomes systems literate.

Table 7.3.

Phase Three Interview Protocols

Interview Purpose 1: Member Checking a Definition of Systems Literacy
I will present each interviewee with a brief summary of my working definition of systems literacy before asking these or similar questions: 1. What is your general impression/initial reaction to this definition? 2. Does this definition resonate with your experiences studying and working with complexity or complex systems? 3. Are there elements of the definition that really work for you? 4. Are there elements that seem to miss the mark? 5. Is anything missing?

Interview Purpose 2: How One Becomes Systems Literate

1. Based on that definition, would you describe yourself as systems literate?
2. If so, how did you develop that literacy?
3. Were there any elements of your early life that you believe contributed to that literacy?
4. To what extent do you feel you developed your systems literacy through your school experiences?
5. To what extent did you develop systems knowledge and skills outside of your formal education?
6. In terms of developing systems literacy, were any aspects of your formal education less effective or even counter-productive?
7. Do you remember when you were first formally introduced to the concept of complex systems? What was the context? What impact did that new way of looking at systems have on you?