Northeast Journal of Complex Systems (NEJCS)

Volume 3 | Number 2 Article 1

March 2021

Adventuring into Complexity by Exploring Data: From Complicity to Sustainability

Tim Lutz
West Chester University, tlutz@wcupa.edu

Adventuring into Complexity by Exploring Data: From Complicity to Sustainability

Tim Lutz
West Chester University, West Chester, PA
tlutz@wcupa.edu

Abstract

Problems of sustainability are typically represented by major present-day challenges such as climate change, biodiversity loss, and environmental and social injustice. Framed this way, sustainable lives and societies depend on finding solutions to each problem. From another perspective, there is only one problem behind them all, stated by Gregory Bateson as: "…the difference between how nature works and the way people think," and complexity provides a way to define and approach this problem. I extend Edgar Morin's conceptions of restricted and general complexity into pedagogy to address problems of simplicity and reductionist teaching. The proposed pedagogy is based on long experience teaching a data-oriented course in which I engage geoscience majors in exploring data rather than in finding answers. They use data tools that emphasize visual understandings over quantitative models and the value of multiple possibilities over a single certainty. The tools, teaching and assessments bring complicity, the entanglement of the nominally objective with the subjective, to the fore so that students develop understandings of the phantom objectivity that characterizes "the way people think." I suggest that complexity-oriented learning based on data exploration can be adapted to other disciplines and even used in non-academic areas since information in the modern world is strongly reliant on quantitative data.

1. Introduction

Living on earth inevitably engages us with complex systems. However, Western science and its industrial applications embraced simplicity and reduction as validating principles, which enabled modern cultures to develop restrictions and freedoms different from those in other living systems. As human understandings of life diverged from the fundamental and essential lessons of complexity contained in our biologic and geologic history, the catalog of destructive patterns came to make up the standard problems of unsustainability: human overpopulation, inequality of the human experience, loss of biologic diversity, pollution, climate change. The pursuit of simplicity caused a radical separation of people from nature and, at a more fundamental level, the separation of subject and object. Mutilating a complex system, such as an organism or an ecosystem, certainly damages it and can eventually kill it. The object-subject divide in our culture is a comparable mutilation, a cutting apart of the relationships among people and planetary systems; unsustainability is the outcome of the mutilation. The identity of complex systems is based in the integrity of their coevolved relationships among constituents. What we lost in modernity is a sense of our *participation* in complex systems (Berman, 1981, pp. 139-144). Essential correspondences between human values and the values embodied in the sustainable operation of the entire planet must be restored.

Morin's (2007) conception of general complexity acknowledges the full participation of humans in complex systems. This paper explores how people participate – are *complicit* – when studying complex systems. Decisions have to be made – about variables, boundaries, restrictions, and so forth – introducing an element of ethical choice (Cilliers, 2000, Preiser et al., 2013, Woermann & Cilliers, 2012). Furthermore, these choices are immersed in a cultural history that conditions all decisions. Complicity refers to the way that researchers are always "entangled in the phenomena researched. Researchers are aspects of even grander systems, shaped by and contributing to the shapes of the phenomena in ways and to extents that they simply cannot know" (Davis and Sumara, 2006, p. 16). The problems of complexity as they relate to sustainability are ones that relate to complicity and the ethics of modeling systems in a participatory rather than an isolating way.

"Changing the culture" has become a common trope in all varieties of organizational sustainability, including in education, an important means of transmitting cultural attitudes. Currently, education does not escape problems of simplification and the subject-object divide; it inculcates them (Davis et al., 2015). For example, the Association for the Advancement of Sustainability in Higher Education (AASHE) assesses "sustainability culture" as a part of its "Sustainability Tracking, Assessment and Rating System" (AASHE, 2019). However, AASHE's system is based on relatively superficial evidence such as awareness of environmental issues and participation in sustainability-oriented programs, while a search of the AASHE website yields few hits on "complexity;" and the word seems to be used as a synonym for "complicated." The efforts of AASHE have environmental and social value but a culture of education that embraces complexity is not yet part of the vision. A rich literature creates the fundamental knowledge base on historical and conceptual aspects of complexity and sustainability in education (e.g., Davis et al., 2015; Doll et al., 2008; Peter & Swilling, 2014). However, there remains a need for transformative educational practices. In this paper, I propose a pedagogy based on the above philosophical concepts that centers student decision-making and reflection to illuminate the complexity of Earth systems and that engages the complicity of people to develop a more sustainable world.

Kagan (2019, p. 157) sees sustainability research as responding to "the double challenge of uncovering the complexity of a globally, locally, and historically unsustainable development path, and of contributing to a search process for more sustainable development paths for humanity." This paper responds to the first challenge by presenting a philosophical perspective using the lens of complexity and complicity to illuminate the problems of unsustainability. I build on the theories of Edgar Morin, Paul Cilliers, and their collaborators to provide insights because these authors recognize that regaining a participatory awareness is essential. Other influential complexity theories such as self-organized criticality (Bak, 1996) and fitness landscapes (Kauffman, 1995) have proven valuable to illuminate complexity in geophysics and ecology, respectively, but have not yet contributed toward understandings of complicity. My contribution to the second challenge applies a complexity-complicity perspective to transform a geoscience course that trains University students to think about and interpret scientific data. Major problems of unsustainability such as climate change, soil erosion, pollution, water resources, and environmental hazards are all components of standard geoscience curricula and all are enmeshed in the complex interactions of natural systems and human cultures. As I became more attuned to complexity, I began to see how my approach to data could be further transformed to teach students a different, complex way of thinking about earth, science, and themselves as scientists and human beings.

2. Restoring complexity and complicity

2.1 The problem of simplicity

In the 17th century Western cultures began to develop ways of observing the world that created a new form of information: digital data, represented by numeric quantities (Berman, 1981). Digital data made it feasible for Western science to develop mathematical relationships to describe natural phenomena (e.g., gravitation), which became codified as "universal laws." From these laws, predictions could be made, and as such laws found greater and greater application over time the necessity for data to feed them grew, as did the technological capabilities to collect data and to analyze them to obtain useful results. Digital data are now a typical way in which many of us receive information about our world. The way we characterize such fundamentals as our health (blood pressure, cholesterol level), our education (test scores, GPAs), our economy (GDP, market indices), our online social connections (friends, hits, likes), our food (calories, nutrient content), our climate (GHG levels, temperature), and the severity of a pandemic (positive cases, attributed deaths) – all these and many more have their "numbers."

Digital data allowed science to develop mathematical and statistical means of reducing complex systems to simple models based on a strategy of finding principles that are universal, ahistorical, and non-contingent (Cilliers, 2010). Our modus operandi has been to distance and to separate ourselves from complexity by setting "simplicity" as our goal. One of Isaac Newton's metaphysical assumptions was that 'Nature is pleased with simplicity' (Doll, 2012, p. 15) and he stated that 'Truth is ever to be found in simplicity, and not in the multiplicity and confusion of things' (Manuel, 1974, p. 120). The oft quoted, "Everything should be made as simple as possible, but no simpler" is a paraphrase of Albert Einstein (Robinson, 2018). The long-lived notion of Occam's Razor has been interpreted to mean that simpler solutions are not only "better" from some operational perspective, but that simplicity is intrinsically truth indicative (Edmonds, 2007). The pursuit of simplicity caused a radical separation of people from nature and, at a more fundamental level, the separation of subject and object and a loss of a sense of participation and complicity. Gregory Bateson referred to the implications of this loss for sustainability when he said, "The major problems of the world result from the difference between the way people think and the way nature works" (Bateson, 2011).

The integration of simplicity in modeling the world has profound implications for sustainability. Simplicity takes the hallmarks of complexity – context, history, indeterminacy, and complicity – as problems to be solved. "Good science" values simplicity, for example, by preferring controlled experiments to suppress context and history, by setting certainty and predictability as goals despite indeterminacy, and by elevating the myth of the objective observer to remove the "I" of participation. Highly restricted models that appear simple tacitly defer the unknown and unmodeled behaviors that escape the models as the responsibility of society at large. Pilkey & Pilkey-Jarvis (2007) and Pilkey et al. (2013) describe how oversimplified models of coastlines failed to successfully represent natural complexity. Their main example shows how models of change on shorelines have been misapplied, with the perverse result that "models have become entrenched in coastal engineering practice and are now a standard weapon in society's assault on the world's coasts" (Pilkey et al., 2013, p. 135). The capacity to collect and process data in ever more computationally sophisticated ways creates an illusion that failed models only need more data for further refinement and perfection. The promise of simplicity to yield ever better prediction and control, if we just have more data, creates unrealistic scientific and societal expectations that become difficult to abandon.

Simplicity also creates a false sense that people are separate from the world and that values need only be framed within a human context; e.g., genuine valuation of the integrity of earth's complex systems is replaced by the material and economic value of resources. Values relating to emergent aspects of earth, such as awe of nature and feelings of kinship with other lifeforms, need to be rediscovered (Lutz & Srogi, 2010). Data and facts have become more powerful than values in shaping culture. Moore and Nelson (2010) claim that "Western society is very good at facts. We aren't as good at values." The goal of their book, *Moral Ground*, is "the fusion of facts and values… to articulate explicitly the missing moral premise of arguments that can compel us from terrifying facts to powerful obligations and effective actions." Their key to sustainability is the restoration of the systemic integrity of natural systems and human values, essentially calling for a renewed sense of participatory awareness.

The education system is the main means of transmitting ideas about what data are, how they can be studied, and how they can benefit us. Scientists are obligated to "see" the world through data, and science teaching conditions all students, from their early grades, to see data from the same perspective. Consider courses that many students, including non-scientists, take as part of their high school or college education. Students in a physics lab may collect data on how the period of a pendulum depends on its length, and then be asked to graph the data to show how period and length are related. Similarly, students in a geology lab may learn to use a graph and data about the arrival times of two seismic waves traveling at different speeds to find the distance to the earthquake that produced them. In each course the students learn that their results are consistent with accepted physical theories. The larger lesson is that the world is governed by laws, and that the job of data is to reveal those laws. They learn that the role of data analysis – the plotting of data on charts and the fitting of mathematical models -- is to allow even imperfect measurements to home-in on the "actual" values of universal regularities such the laws of gravity and motion. They also learn that there are correct answers that the professor expects to them to know, and this lesson is repeated and reinforced in many other subjects. Physicists and seismologists produce societally useful results and there is value in having students understand the methods of science. But when education adopts a perspective that assumes that there are always "correct" answers to "simple" problems, then that perspective infiltrates many aspects of existence, even those which should be guided by imagination and a creative spirit. Rosen (2019, p. 1) relates how one her art students, in the process of creating a beautifully expressive drawing, paused to ask, "Is this right?"

2.2 How can we escape the problems of simplicity?

Complexity, as Paul Cilliers (2006) notes, isn't something that people recently discovered but rather a way to say how things work and have worked on our planet. Kagan (2010, 2013) proposed the term "autoecopoiesis" to refer to the continual regeneration and evolution of complex systems (poiesis) in ways that balance the needs of a particular part or the self (auto) in relation to the environment or ecosystem (eco). In earth's history we see autoecopoiesis expressed in the co-evolutionary relationships among the living and the nonliving.

The history of life recorded in fossils and DNA is interwoven with changes in the chemistry of the oceans and atmosphere, and even the types of minerals, rocks, and soils that formed at different geologic times. Complex systems are open to flows of energy and information that permit order to be maintained even as the components are altered or replaced at different scales throughout the systems (Capra & Luisi, 2014; Morin, 2008). Edgar Morin (2007) called attention to the essential way that complex systems depend on the transformation of differences along reflexive circuits. For Morin (2008, pp. 72-73), the self is defined not by Descartes' "cogito" but by a more basic operation, the "computo:" any complex system is a "system based on the difference between self and not-self." Gregory Bateson (2002, p. 92) made a similar point when he stated "Information consists of differences that make a difference."

The idea of difference within complex systems is developed by Cilliers (2010), Human & Cilliers (2013), and Preiser et al. (2013), in their philosophical concept of a general economy. "Economy" refers to any system in which the relationships among the components are limited or restricted. These authors note that complex systems in the world are open and that they can exist and function only because they develop differences in the form of dynamic, interactive boundaries. For example, the surface of a pond may seem like a "roof" that confines aquatic organisms below it but interactions through that surface are necessary: gases are exchanged between water and air, rain falls, mayflies are consumed by leaping trout, and herons reach through to pick up minnows. The level of the surface is determined by the interplay of water with its surroundings. So the boundary of water with air restricts the aquatic ecosystem but also connects it and makes it possible. The complex behaviors of an economy include interactions that create excesses, or play, that lead to emergent phenomena or, as it is often stated, a whole that can exceed the sum of its parts (Human & Cilliers, 2013). On the other hand, the boundaries limit some possibilities so that, simultaneously, the economy can be less than the sum of its parts (Morin, 2007). Cilliers (2001) argues that our ideas about boundaries should not be restricted to those that exist physically but should include economies of thought. For example, academic disciplines have their boundaries and each discipline adjusts its identity in interaction with others; a market functions because it defines what is valuable (e.g., a good or a bad) and what is not (e.g., an externality). As the boundaries of general economies change dynamically, they develop a degree of stability that maintains the structure of the system and allows the system to develop an identity (e.g., "pond", "market", "discipline") (Cilliers, 2010).

Our models of systems – where "model" can mean any understanding of the world we express, whether formal or informal – are also complex economies, and we participate – are complicit – in setting the boundaries of the economy. "By drawing boundaries, we create the 'space' which allows us to say something about the system. This space is not static but a site of action. It is in this space that we create differences, including the difference between inside and outside, which allow us to create models and indeed to act in the world" (Cilliers, 2010, p. 37). If the modeler is oriented toward simplicity and prediction then restrictions will be used to exclude complexity and limit the play of the model, creating a sense of certainty that can be illusory, false, or even disastrous (Pilkey et al., 2013). Models that reveal more of the play of the system will be less suitable for prediction but may greatly enhance the overall understanding of the system.

I propose a pedagogy based on the above philosophical concepts that centers student decision-making and reflection to illuminate the complexity of Earth systems and the complicity of the modeler in applying restrictions to those systems. About twenty-five years ago I began to teach a course about data and data analysis for upper-level undergraduates and graduate students in the geoscience program at West Chester University. As I learned about complexity and complicity I realized that my course is a model for how information is used by a system – and that the model might be changed so that analysis of digital data leads to fruitful discoveries and understanding of systems, and not inevitably to simplicity and reduction (Baker, 2017; Burt and McDonnell, 2015). Could my course, or any course that utilizes data, model the behaviors that promote a culture of sustainability? The remainder of this paper describes my affirmative answer to that question.

3. A pedagogy of complexity and complicity

The tools we use to study data and the ways we learn to use them are a means to change our experience. This practical approach echoes Buckminster Fuller: "If you want to change how someone thinks, give up; you cannot change how another thinks. Give them a tool, the use of which will lead them to think differently" (quoted by P.M. Senge in Ehrenfeld, 2008, p. xvi). This is the thought motivating this paper: to give students tools that, when used, will lead them to think differently about complexity and their complicity as analysts. To be understood and to prove valuable to students the tools need to be taught in a particular field of study; but their character cannot be tied to just one field of study. Appropriate data tools in any discipline can begin to move our understandings of data from simple modes of interpretation to more complex ones. Those movements can include:

- From objective knowledge toward subjective discovery (complicity)
- From consideration of single scales (space, time, level) toward multiple scales
- From isolated facts toward contextual understandings
- From change in universal time toward change as system time

- From unique outcomes toward multiple perspectives
- From quantified results toward patterns

Geoscientists by and large do not perform controlled experiments. They collect data where and when they can and utilize data of a variety of kinds and from sources with different and possibly poorly characterized qualities. The ability to find patterns, differences, and correspondences among data is more useful than the ability to apply statistical models that aim for certainty-bounded outcomes and predictive power. The complexity of the natural systems we study and our complicity in making the choices and judgments needed to find the patterns, differences, and correspondences provide the "play."

When data are presented as quantities it is easy for their representation to create an impression of facts in isolation from context, and I find that my students are conditioned to think of data as isolated nuggets of objective information. It's an easy conclusion to reach since that is the way each value is represented in a spreadsheet's cell; each symbol on a graph represents one of those nuggets. They have learned from a lifetime (for them) of experience that exams can ask them to remember facts without necessarily recognizing the context in which those facts were obtained. This contrasts with complexity thinking, where "the facts of a subject exist not in isolation, separate from one another, but acquire their validity through their contextual relationship with other facts, with the discipline in which they are embedded, and with their relation to those experiencing the facts" (Doll, 2012, p. 15). To lead students to reconsider their reductionist views my course, Geometrics, is based on using the tools of exploratory data analysis (EDA; Tukey, 1977) and thus more on visual interpretation than on quantitative results. EDA is not intrinsically concerned with complexity, especially if only considered as a preliminary to standard statistical analysis (Tukey, 1977). However, it has several strengths as a component of a course oriented toward complexity thinking.

1. EDA procedures engage investigators in making choices, and those choices give them responsibility for the decisions they make. Tukey (1977) emphasizes that EDA is an exploratory process that depends on the judgment of the analyst; data exploration develops judgment.
2. By focusing on the visual, EDA de-emphasizes reliance on mathematical forms that lead toward plugging data into predictive models and that then tend to short-circuit full exploration of the data (Anscombe, 1973).
3. Charts can be effectively shared with others because visual representation doesn't require the same degree of technical knowledge as a mathematical equation. The work of individuals can be arranged spatially to give teams of investigators the ability

to compare their choices and the patterns they find (e.g., small multiples, Grady, 2005; Tufte, 1983, 1997)

4. Visual displays easily allow multiple understandings of the same data to be found and considered at the same time, emphasizing the multiplicity that characterizes complex systems.
5. Charts can be highly effective in making insights into data obvious. "Visualization… stresses a penetrating look at the structure of data. Sometimes visualization can fully replace the need for probabilistic inference. We visualize data effectively and suddenly, there is what Joseph Berkson called *interocular traumatic impact*: a conclusion that hits us between the eyes" (Cleveland, 1993, p. 12).

To be attuned to the possibilities of the play in a general economy, the researcher has to find ways to "play" with data, that is, to find ways of interacting with data that don't follow cut-and-dried rules of analysis but that make the judgment of the analyst part of the way the system is understood. To allow my students the freedom to play easily, I avoid placing emphasis on students' technical abilities to "do the calculations" or "use the correct formulas." Instead, I provide Excel workbooks I call "Data explorers" that carry out various types of play and that create visual representations of the data. Each explorer has one or more analytical parameters that students can change. Students can select from various sets of data and even provide data of their own. The values and data they choose immediately creates charts or tables that show the effect of the choice made. Learning occurs when students compare the charts they make and observe how their choice of parameters makes a difference. In the following section I explain several examples of "data explorers" and the play that can result.

It is essential that data tools are supported by pedagogy that explains and models complex play because students have been trained to think of working with data as a "serious" activity. When students are first presented with a data set and a "data explorer" and told to play they typically respond with expressions registering confusion or distress. Rosen (2019, p. 2) points to this discomfort as a necessary part of complexity learning: "For students generally drilled into reproducing 'the' right answer, being asked to think pluralistically and generatively is liberating yet also stressful." As children's creativity can be diminished when deprived of free-play in the outdoors, my students have been similarly deprived by a lack of experience with Excel or other data tools as platforms for "free-play" with data: exploring, discovering, and adventuring with data. I deliberately allow a polysemy for the term "data explorer" in the classroom: it can mean the Excel tool, but it can also mean the student. The confusion that can result always serves to renew reflection on how the use of the tool and the learning of the user are related.

Many of my students know about inductive and deductive reasoning but few know abductive reasoning, a vital but frequently ignored aspect of science developed by scientist and philosopher Charles S. Peirce (Doll, 2012). Abduction is playful thought that arises from surprise or doubt and is oriented toward fruitful discovery, or uberty (Doll, 2012; Baker, 2017). Abduction is key in the process of recognizing patterns that defy or are inconsistent with our expectations, and thus guide how scientists form new hypotheses. Visualization is critical to abduction: "We discover unimagined effects, and we challenge imagined ones" (Cleveland, 1993, p.1). Data explorers provide a practical means for students to be surprised at what their charts show.

4. Data Explorers

4.1 Moving average explorer

Students in my course are familiar with the concept of averaging quantities over time. For example, the U.S. National Weather Service typically reports averages of weather data over a recent 30-year span; for the last ten years, the 30-year average precipitation was based on data spanning 1981-2010; after 2020, the average will be based on data from 1991-2020. This practice restricts the average to a single value, and thus this model of the data has no play. We can make a definitive statement of high precision, say, "The average precipitation was 3.05 inches per month," but the size and pattern of variability of precipitation "outside" the model, and its meaning for us, is not addressed.

The moving average explorer promotes a more playful approach by calculating the moving average for any given span. For example, if the averaging span was three months, then the average for February 2019 would be based on data from January 2019, February 2019, and March 2019; the average for March 2019 would be based on February 2019, March 2019, and April 2019, and so on. The explorer includes data for precipitation, streamflow, the areal extent of Arctic sea ice, the CO_2 content of the atmosphere, and the local change in sea level caused by a tsunami.

An assignment using this data explorer asks students to choose several different moving average spans. Students are encouraged to experiment: how does the output chart change when different averaging spans are selected? As they explore, they choose three charts they find interesting to upload so that everyone can see. I ask some students to show their charts and to explain why they selected them. What was interesting about them? How are they different from one another? From discussing our results they find that the moving average window filters out variability on time scales shorter than the window span. For example, Figure 1 shows charts of precipitation data using three different spans that reveal variability on different time scales.

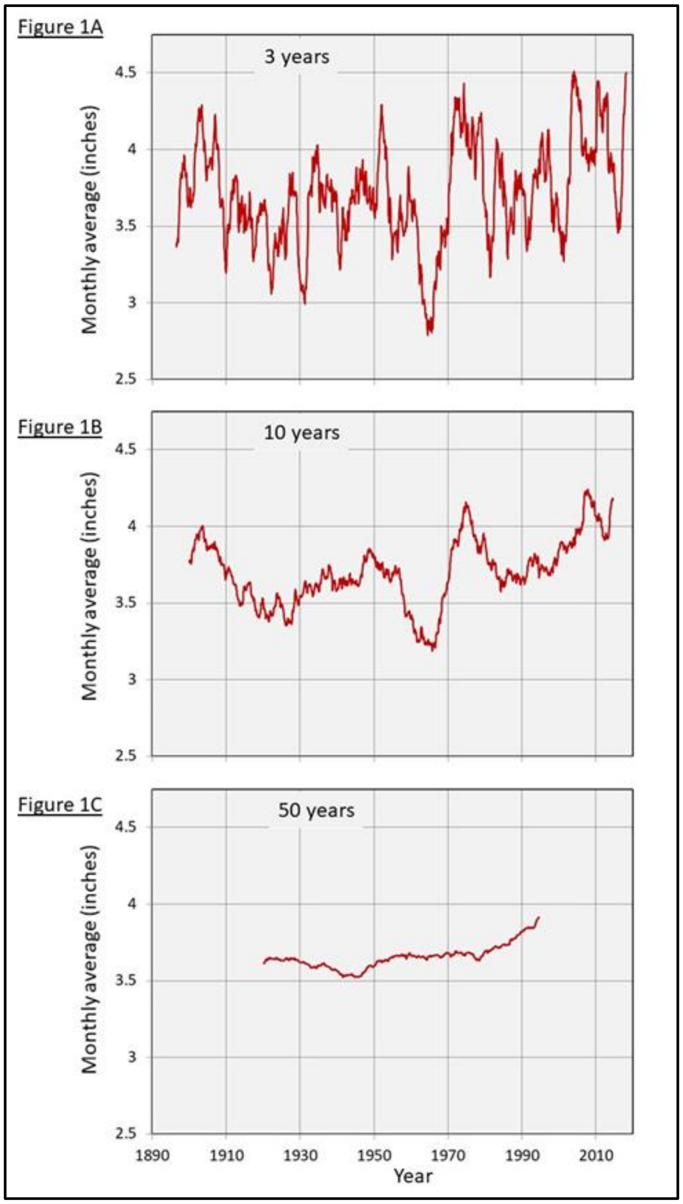

Figure 1. The charts are based on monthly precipitation rates (inches/month) for Pennsylvania Climate Division #3, Southeastern Piedmont, from January 1895 through August 2019. Data for every one of the 344 climate divisions in the conterminous U.S. are available from the National Centers for Environmental Information (https://www.ncdc.noaa.gov/). The red line in each chart is the output calculated by the moving average explorer referred to in the text. The moving average window in each part is: 1A, 3 years; 1B, 10 years; 1C, 50 years. The vertical scale is the same on all parts.

Figure 1A (3-year span) reveals multi-year fluctuations ; the rate of precipitation is highly variable, and nothing like the single value of the thirty-year average. Figure 1B (10-year span) emphasizes longer term trends and larger deviations, such as the drought that occurred in the 1960's. Figure 1C (50-year span) shows slow changes, including a recent upward trend, consistent with predictions based on climate change models.

During class discussion I emphasize that: 1) all of the charts use the same data; 2) the differences among the charts result from the choices they made for the span; 3) there is no single average or span that is "right"; and 4) at each scale features are revealed that are potentially useful for understanding the natural systems and how people might be related to them. Understandings that emerge from this approach are:

- the researcher is complicit in making the choices that lead to a specific result and the value of the choices cannot be known a priori but emerges from the play;

- the data contain features across a range of scales, and
- at each scale we find features that can surprise us, that raise questions and could help frame hypotheses, reinforcing the abductive reasoning process.

4.2 Rotation explorer

Geology students are familiar with the idea that earthquakes at tectonic boundaries occur in a zone that slants downward; this is the basis for the concept of plate subduction, where the lithosphere of one plate descends into the mantle beneath another. They have seen schematic diagrams showing this ideal, slanting arrangement from their earliest geology courses (Figure 2A). My rotation explorer contains the geographic locations, depths and magnitudes of earthquakes in the Tonga trench region so that they can find how the ideal view comes about. Students select the direction in which the three-dimensional distribution of earthquakes is viewed by actively rotating the data around a vertical axis. Figure 2 gives two examples of what they can see as they change the view angle. From one perspective (Figure 2B) the earthquakes appear to be distributed from the surface to about 700 km depth in a "curtain" arrangement in which the slanting subduction zone pattern cannot be seen. As they rotate the data, students find a view direction in which the "classic" subduction zone is obvious (Figure 2C). To their surprise, they learn that even in that view there is much about the subduction zone that is not like the ideal picture, and that small differences in the rotation angle reveal new information. Views not showing the ideal subduction arrangement reveal intriguing features such as vertical undulations in the earthquake "curtain," inhomogeneous distributions of earthquakes with depth, and "knots" of more intense earthquake activity within the subduction zone.

Over years of providing this earthquake explorer to students, I've found that its effect is long-lasting. At alumni events it is mentioned as one of the most memorable experiences in my course, and former students who are teachers tell me they use it in their own courses. The lasting effect of this calculator does not come from discovering the unknown; the concept of the subduction zone is already known to them. It comes from the experience of actively creating new perspectives for themselves. The intrinsic desire of people to pick up unfamiliar things and to turn them around to see something interesting is at play. This outcome speaks to the potential for people to be engaged by tools that make them complicit in the discovery process and that open their minds to their participation in a complex system of exploration.

DOI: 10.22191/nejcs/vol3/iss2/1

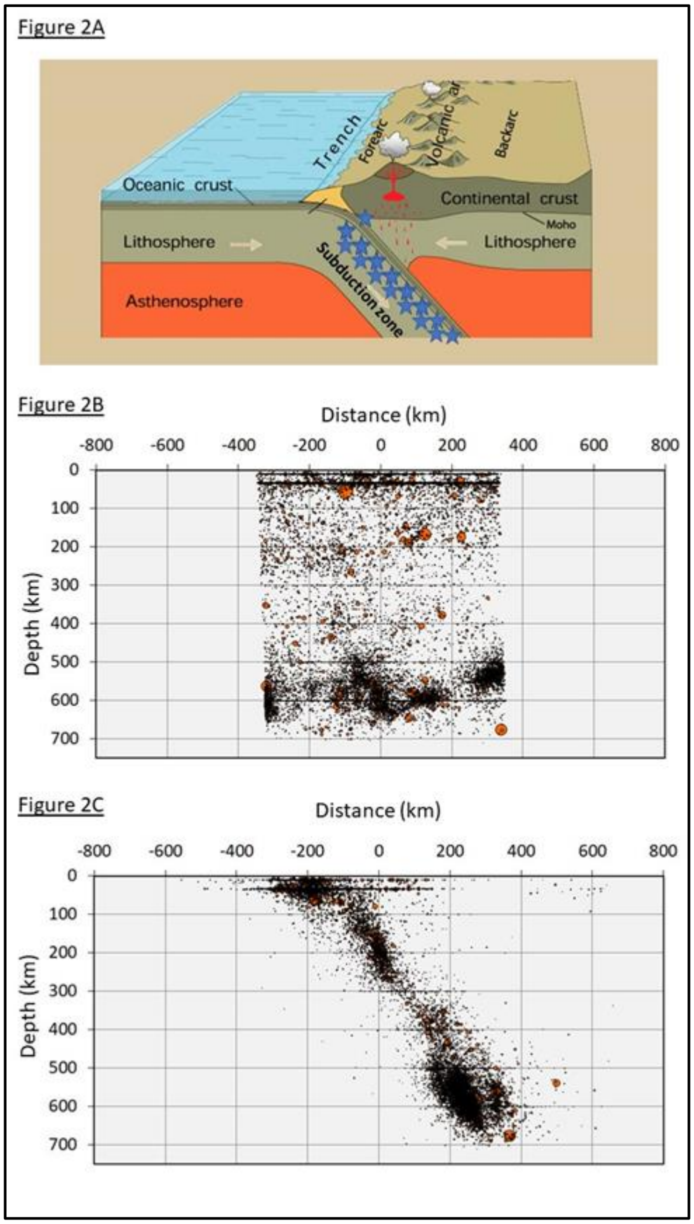

Figure 2. The diagram in 2A is modified from an image posted on the USGS website (https://www.usgs.gov/media/images/subduction-fault-zone-diagram). Blue stars indicate the region in which earthquakes originate. Figures 2B & 2C show 14,918 earthquakes in the Tonga region; geographic locations, depths and magnitudes of earthquakes from 1973 through October 2016 downloaded from the USGS (http://neic.usgs.gov/neis/epic/epic.html). In 2B the view is to the east; in 2C the view is to the south.

4.3 Co-series explorer

Students (and many of us) typically think of everything changing "with" time, the nearly unavoidable outcome of science that formulates mathematical models in which time is the "independent" variable and other variables are "dependent" on time. For example, the time-dependence of streamflow is portrayed in diagrams in every textbook that includes stream hydrology. Standard charts of a variable versus time (Figure 3A) reinforce two misunderstandings about complex systems: 1) that some generalized, universal "time" is controlling the stream (Cilliers, 2006) and 2) that each characteristic is dependent only on time and is therefore independent of other variables. Research scientists may "actually" understand the interconnected, systemic nature of the stream but are satisfied to represent their understanding in simple terms.

The co-series data explorer challenges and opens up students'

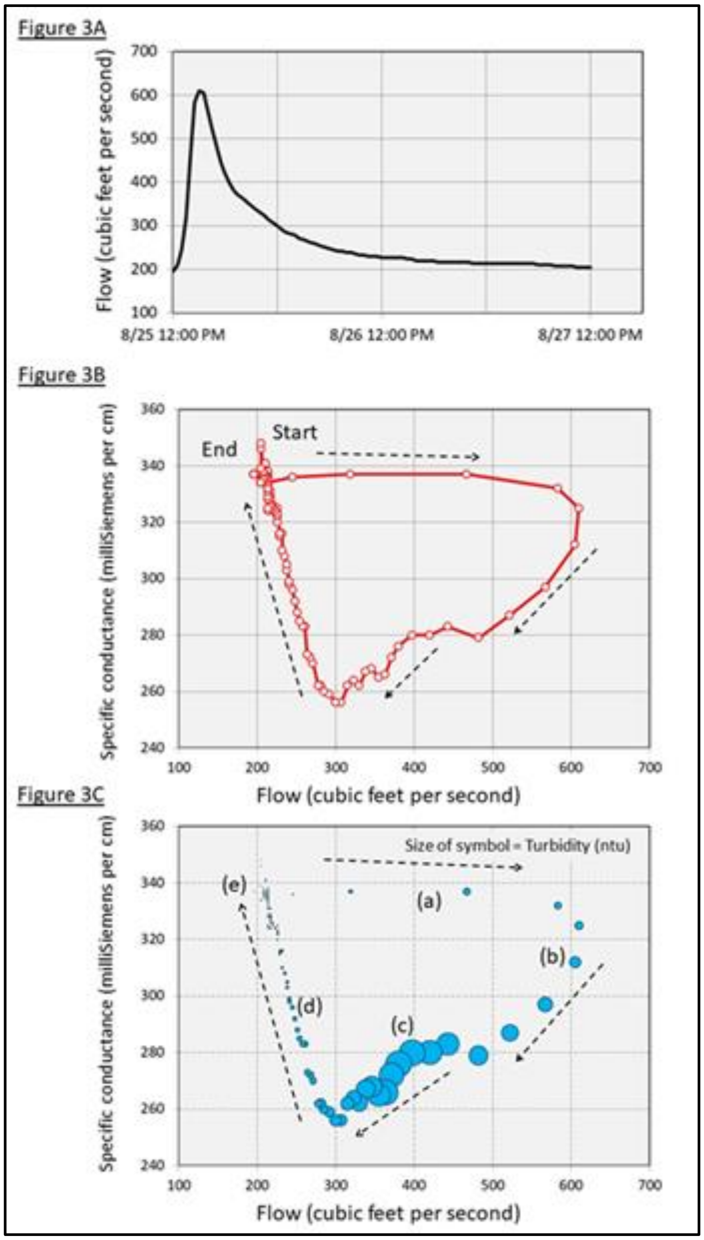

Figure 3. The charts are based on data collected at the USGS gaging station on the Brandywine Creek at Chadds Ford, PA (https://waterdata.usgs.gov/pa/nwis/) from noon on 8/25/2011 to noon on 8/27/2011.

understandings using data from a stream such as volumetric streamflow, conductance (concentration of ions dissolved in the water), and turbidity ("muddiness" of the water from transported sediment). The explorer allows students to select one character of the stream (e.g., conductance) and show its variation plotted directly with another aspect (e.g., stream flow); and also to select the range of measurements to show. Time doesn't occupy its usual privileged position on the x axis of the charts (Figure 3B). Since the charts do not automatically indicate the sequence of change, students learn to indicate time by adding annotation text and arrows, as shown on Figure 3B. The symbols represent measurements made at equal intervals (30-minutes) over a 48-hour period; a line connects symbols to emphasize the continuity of change. The lengths of line segments between symbols indicate the relative rate of change (conductance relative to streamflow in Figure 3B). Students can readily see that after rainfall, streamflow increases quickly, as indicated on the chart at 'Start', while conductance changes little; then conductance decreases as stream flow begins to decrease; both begin to change more slowly, conductance reaches a minimum while flow is still decreasing; after which conductance slowly returns to its starting value ('End') with little additional decrease in flow. This diagram directs attention to correlated change and changes in rate of change, aspects of the data that are hard to see if conductance and flow are individually charted against time, and yet which are essential to understand complex systems.

Figure 3C shows that adding a third variable (turbidity, or the muddiness of the water) using the size of a chart symbol increases understanding by showing how three characteristics are interrelated through time. The asynchronous and dynamically changing flow, conductivity, and turbidity of the stream raise a question: how are these three variables connected? Trying to understand the chart makes us think outward from the stream to the larger watershed system where rain falls, runs to the stream and increases flow (a); as rain water dilutes the stream, conductance drops, even as the stream flow begins to wane (b); sediment carried into the stream makes it muddy as flow continues to decrease (c); as runoff diminishes and the stream is fed more by groundwater, conductance slowly rises and turbidity decreases (d); after two days the stream clears and returns to near its starting state (e). Conductance and turbidity do not march in lockstep with streamflow; there is a delay, a hysteresis response that is like a dance by which the stream "remembers" the rainfall and its watershed, and then "forgets" as it returns to its initial state. Complex systems embody memory, and memory is a process of selection that includes forgetting. "The identity of a system is… its collection of dynamic memories. In order for it to be a system at all, a system that has its own identity, that can react to the environment and not just mirror it, a certain hysteresis is required" (Cilliers, 2006, p. 3). The co-series chart makes the memory of the stream visible. For the charts to make sense in this way the student data explorer also has to provide their judgment and understanding via the annotation labels and arrows on the chart.

5. Complicity and the creative imagination in science education: Arts Based Research

Each data explorer exemplifies the way play helps create understanding of complex systems. The students can see themselves as parts of the systems they explore: it's through their interventions in selecting, windowing, rotating, and otherwise exercising their judgment that they create meaning. There are few fixed rules to follow or correct outcomes to achieve; by learning to play with the restrictions they place on the data they become explorers of the particular data sets they have; by reflecting on their play they are aware of their complicity; and they are more prepared to become adventurers in all the data systems they will encounter in their nonscientific and private lives, too. The intention of the data explorers is to engage and practice many of the habits of mind selected by Rosen (2019) for her 11th grade English class, "Methods of Inquiry": curiosity, multiple perspectives, close observation, playfulness, risk taking, collaboration, uncertainty tolerance, reflection, and persistence.

Data explorer tools provide an in-class experience that emphasizes the provisional nature of scientific research and the "significant role of uncertainty in any process of coming to know…" (Rosen, 2019, p. 2). Within the traditional framework of science, exploring a data set can suggest multiple explanations for unexpected patterns, an important part of the abductive reasoning process that leads to new hypotheses (Baker, 2017; Doll, 2012). Students introduced to data from a complexity perspective sometimes feel the need to "defend" science because introducing choice and judgment into the process of using data seems to threaten the validity of what many see themselves doing in their future lives: collecting accurate data in the field or lab so that those data can be useful to society. An important understanding for these students to achieve is that there is nothing wrong with applying highly restrictive modeling to data, say to make a calculation to predict the height of a levee needed to protect people from floods (Cilliers, 2000). The problem is when we forget that the assumptions we need to make about our data, models, ourselves, and the world are really assumptions. Everyone engaged with data is responsible for recognizing the boundaries of the economies in which data are produced, interpreted, and used.

Students also need to be reminded that the data supplied in their data explorer is not just limited by its accuracy, precision, and apparent completeness but by what is missing, by what was outside the vision of the systems that produced the data. Within science, for example, the data we have may be limited by the budget we have, by the number of hours in a day, by the priorities of employers and funding agencies, by the value that society places on the field of study, and particularly by what society does not value because that may create inequalities and injustices (e.g., Criado-Perez, 2019). It is not for the scientist to comprehensively address such issues but to remember that they exist and that the consequences of their research will be less certain and will possibly extend much further than they can imagine: the consequences of a restricted model depend on what is left out as well as what is taken in. A good example is provided by climate change science. Data showing rising CO_2 in the atmosphere go back over half a century. Models based on these data and on other greenhouse gases (GHG) predict dire consequences for humanity unless GHG emissions are reduced to near-zero in just a few years (e.g., Ripple et al., 2017). Scientists are frustrated that people, individually and politically, have not responded more quickly because "inside" science the necessity to reduce emissions seems quite clear. But centuries of restricting science to the objective interpretation of natural phenomena has disconnected science from the mainstream of human experience and concern. "The creation of meaning involves more than narrowly-defined cognitive (i.e., logico-deductive) aspects of climate change; it calls for the inclusion of ethical, affective and aesthetic knowledges, which affect how humans interpret and assign value to certain aspects of the world" (Galafassi et al., 2018, p. 73).

This approach has much in common with the ideas of Kagan (2011, 2017) and Heinrichs & Kagan (2019) regarding arts-based research (ABR). ABR had "its roots in early attempts… to avoid scientific reductionism by using methods of the creative arts to gain more holistic insights into human experiences and practices" (Heinrichs & Kagan, 2019, p. 434). Examples include the way Chris Jordan (2008) creates images to represent quantities that are otherwise large and unfathomable and how Nathalie Miebach (2011) translates weather data into complex sculptures and musical scores. ABR goes beyond these approaches because it seeks to provide a "methodology in which scientific and artistic ways of sense-making converge" (Heinrichs & Kagan, 2019, p. 434). One of ABR's essential values is in the continual, ongoing experience of bringing together scientific and artistic ways of making sense, not in a final product that can be interpreted as "art" (Heinrichs & Kagan, 2019). ABR is about exploration while allowing ambiguity and ambivalence, and about the critical awareness of the subjective self of the researcher as an author and as a story-teller. This analysis echoes the work of Edward Tufte (1983, 1990, 1997, 2006). Grady (2005, p. 4/27) points out that "Tufte's oeuvre is permeated by an ethos that makes analytic work an aesthetic pleasure. In his view, sound analysis requires not only a consistent aesthetic but also that the task itself be art. In so doing, Tufte challenges the various dualisms that see art as completely distinct from work, science, and other spheres of human purpose." Data explorer tools, like good mechanical tools, can be a pleasure to use (Grady, 2005): we can be carried forward by the "pleasurable activity of the journey itself" (Samuel Taylor Coleridge, quoted in Dewey, 2005, p. 4). The lessons learned from such tools are not only about the data but also about the habits of mind and practices that create the visualizations. "Education should encourage the natural aptitude of the mind to set and solve essential problems and, reciprocally, should stimulate full exercise of general intelligence. This full exercise requires the free exercise of the most well-distributed, most vigorous faculty of children and adolescents – curiosity…" (Morin, 1999, p. 15).

6. Learning outcomes and assessment philosophy

The key learning outcomes for complexity and complicity are understandings about how humans are implicated in the results that data produce and that exploration allows the diverse ideas of different explorers to contribute to discussion. It is the richness of the exploration and the discussion it produces that is the aim, not a correct answer or analysis. Assignments based on data explorers let me make the point that I have nothing "special" to teach the students about complexity. Though the results of each explorer are no longer a total surprise to me, I am intrigued by what my students find in the data I give them. The classroom is the place for me to show that I, too, am "open to surprises and to engage in ongoing cycles of exploration…" (Rosen, 2019, p. 4).

I design the assessment of students to be consistent with the course's mission. Participation and completion of assignments is essential: my students need to adventure into the terrain represented by each data set and data explorer tool. The "correctness" of the results they obtain is not. I want my students to remember and reflect on their complicity in learning about complexity as well as the specific aspects of geology they encounter. The major evaluation for my course is a portfolio that each student constructs during the semester that contains a collection of their assignments, class notes, and reflections on the course. I specify that these be present and that each student makes their own decision about what they will include and the way they will balance the outcomes for geology and for complicity. They have to explain their decisions in the introduction to their portfolio. The portfolio, then, is a model the students construct of the course; they can't include everything, they need to purposefully restrict their model and be conscious of what they put in and what they leave out.

When possibilities of thinking or acting differently in support of sustainability are *merely presented* to students, they frequently respond with discomfort or objection. Rather, my course gives them tools such as the data explorers to directly engage them in *thinking* differently. Despite what I intend my students to learn about complexity and sustainability I have to recognize that they are already engaged on a journey guided by personal and societal motives. But what may be most important is that humanity has access to a diversity of ways of understanding difference (Cilliers, 2010), and data adventures help clarify and strengthen a neglected way to carry out the most basic action of complex systems, the 'computo'.

7. Final thoughts

Advances in modern life seem to be all about trying to overcome problems of complexity, whether those problems are seen as natural or social. Following the lead of Edgar Morin (2007) and Paul Cilliers (2010), I posit that our understanding of the complexities of systems is incomplete unless the complicity of human modelers who make choices and judgments is acknowledged. "Cultures of sustainability are a matter of constant self-critical exploration. They require continuous reactualization of reflexive competences. For this reason they demand an artful practice of life" (Kagan, 2010, p. 1100) and a key outcome of an artful practice of life is the development of imagination and the formation of social imaginaries (Kagan, 2019). For Kagan, "imagination" refers to an individual or social process by which reality is shaped and in which possible shapes of one's environment emerge; an "imaginary" is "like a cognitive and cultural humus from which more articulate cultural constructs such as visions, narratives, discourses and utopias can grow and where they can take roots" (Kagan, 2019, p. 161). Though, as scientists, my students will be called to draw practical meaning from data, they also are learning a lesson about sustainability. Using the visualizations their data explorers provide they practice contemplating the possible shapes of their environment. The process may be difficult: "the grip of what is familiar and fixedly habitual must be broken, even briefly, if imagination is to be liberated" (Rosen, 2016, p. 134).

The aim of the data exploration tools and learning framework I propose is to create a more open set of outcomes in which our experiences develop our judgment and understanding. To make general complexity of interest and of value to my students I restrict my classroom economy. I work with data sets and exploration tools (e.g., moving average, co-series, rotation) that come from my specific history and expertise in geology and statistics. The restrictions are significant, and they lead to a question: "How will the experiences and ideas I present in this paper be meaningful to the readers?" Data – quantitative information in digital form – are spread widely across disciplines and through life. The works of Edward Tufte (1983, 1990, 1997, 2006) contain many examples of data visualization from fields that range from the natural and social sciences to advertising and other aspects of popular culture. We do not need sophisticated computational and visualization software: simple methods, such as a moving average, can engage us in understanding our complicity. Finally, there is no pool of expert knowledge in applied complexity that we have to learn before we can start. As teachers we can build our curiosity and imagination as we adventure with our students.

References

[1] Anscombe, F.J. (1973) Graphs in statistical analysis. *The American Statistician 27*(1), 17-21.

[2] Association for the Advancement of Sustainability in Higher Education (AASHE). (2019). *The Sustainability, Tracking, Assessment & Rating System*. https://stars.aashe.org/

[3] Bak, P. (1996) *How nature works: The science of self-organized criticality*. Springer-Verlag.

[4] Baker, V.R. (2017) Debates – Hypothesis testing in hydrology: Pursuing certainty versus pursuing uberty. *Water Resources Research 53*, 1770-1778.

[5] Bateson, G. (2002) *Mind and nature: A necessary unity*. Hampton Press.

[6] Bateson, N. (Director). (2011) *An ecology of mind: A daughter's portrait of Gregory Bateson* [Film]. Bullfrog Films.
[7] Berman, M. (1981) *The reenchantment of the world*. Cornell University Press.
[8] Burt, T.P. & McDonnell, J.J. (2015) Whither field hydrology? The need for discovery science and outrageous hydrological hypotheses. *Water Resources Research 51*, 5919-5928.
[9] Capra, F. & Luisi, P.L. (2014) *The systems view of life: A unifying vision*. Cambridge University Press.
[10] Cilliers, P. (2000) What can we learn from a theory of complexity? *Emergence 2*(1), 23-33.
[11] Cilliers, P. (2001) Boundaries, hierarchies and networks in complex systems. *International Journal of Innovation Management 5*(2), 135-147.
[12] Cilliers, P. (2006) On the importance of a certain slowness. *Emergence: Complexity and organization*, doi: 10.emerg/10.17357.bd3be2ec507c9e039579778f0452f0a1, 1-6.
[13] Cilliers, P. (2010) Difference, identity, and complexity. *Philosophy Today 54*(1), 55-65.
[14] Cleveland, W.S. (1993) *Visualizing data*. Hobart Press.
[15] Criado Perez, C. (2019) *Invisible women: Data bias in a world designed for men*. Abrams Press.
[16] Davis, B. & Sumara D. (2006) *Complexity and Education: Inquiries into Learning, Teaching, and Research*. Routledge.
[17] Davis, B., Sumara, D. & Luce-Kapler, R. (2015) *Engaging minds: Cultures of education and practices of teaching*. (3rd ed.). Routledge.
[18] Dewey, J. (2005) *Art as experience*. Penguin Group. (Original work published 1934)
[19] Doll Jr., W.E., Fleener, M.J., Trueit, D. & St. Julien, J. (Eds.) (2008) *Chaos, complexity, curriculum, and culture: A conversation*. Peter Lang.
[20] Doll Jr., W.E. (2012) Complexity and the culture of curriculum. *Complicity: An International Journal of Complexity and Education 9*(1), 10-29.
[21] Edmonds, B. (2007) Simplicity is not truth-indicative. In C. Gershenson, D. Aerts & B. Edmonds (Eds.), *Worldviews, Science and Us: Philosophy and Complexity* (pp. 65-80). World Scientific Publishing.
[22] Ehrenfeld, J.R. (2008) *Sustainability by Design: A Subversive Strategy for Transforming Our Consumer Culture*, Yale University Press.
[23] Galafassi, D., Kagan, S., Milkoreit, M., Heras, M., Bilodeau, C., Bourke, S.J., Merrie, A., Guerrero, L., Pétursdóttir, G. & Tàbara, J.D. (2018) 'Raising the temperature': the arts on a warming planet. *Current Opinion in Environmental Sustainability 31*, 71-79.

[24] Grady, J. (2005) Edward Tufte and the promise of a visual social science. In Luc Pauwels (Ed.), *Visual Cultures of Science: Rethinking Representational Practices in Knowledge Building & Science Communication* (pp. 222-265)
[25] Heinrichs, H. & Kagan S. (2019) Artful and sensory sustainability science: Exploring novel methodological perspectives. *Journal of Environmental Management & Sustainability 8*(3), 431-442.
[26] Human, O. & Cilliers, P. (2013) Towards an economy of complexity: Derrida, Morin and Bataille. *Theory, Culture & Society 30*(5), 24-44.
[27] Jordan, C. (2008, February). *Turning powerful stats into art* [Video] TED. https://www.ted.com/talks/chris_jordan_turning_powerful_stats_into_art
[28] Kagan, S. (2010) Cultures of sustainability and the aesthetics of the pattern that connects. *Futures 42*, 1094-1101.
[29] Kagan, S. (2013) *Art and sustainability: Connecting patterns for a culture of complexity*, Bielefeld: transcript, emended ed.
[30] Kagan, S. (2017) Artful sustainability: Queer-convivialist life-art and the artistic turn in sustainability research. *Transdisciplinary Journal of Engineering & Science 8*, 151-168.
[31] Kagan, S. (2019) Proving the world more imaginary? Four approaches to imagining sustainability research. *Österreich Z. Soziol. (Suppl. 2) 44*, 157-178.
[32] Kauffman, S. (1995) *At home in the universe: The search for laws of self-organization and complexity*. Oxford University Press.
[33] Lutz , T. & Srogi, L. (2010) A values framework for students to develop thoughtful attitudes about citizenship and stewardship. *Journal of Geoscience Education* 58 (1), 14-20.
[34] Manuel, F.E. (1974) *The Religion of Isaac Newton*. Quoted from 'Fragments from a Treatise on Revelation", 120.
[35] Miebach, N. (2011, July). *Art made of storms* [Video]. TED. https://www.ted.com/talks/nathalie_miebach_art_made_of_storms
[36] Moore, K.D. & Nelson, M.P. (2010) *Moral ground: Ethical action for a planet in peril*. Trinity University Press.
[37] Morin, E. (1999) *Seven complex lessons in education for the future*. UNESCO.
[38] Morin, E. (2007) Restricted complexity, general complexity. In C. Gershenson, D. Aerts & B. Edmonds (Eds.), *Worldviews, Science and Us: Philosophy and Complexity* (pp. 5-29). World Scientific Publishing.
[39] Morin, E. (2008) *On complexity*. Hampton Press.
[40] Peter, C. & Swilling, M. (2014) Linking complexity and sustainability theories: Implications for modeling sustainability transitions. *Sustainability 6*, 1594-1622.

[41] Pilkey, O. & Pilkey-Jarvis, L. (2007) *Useless arithmetic: Why environmental scientists can't predict the future*. Columbia University Press.
[42] Pilkey, O., Young, R. & Cooper, A. (2013) Quantitative modeling of coastal processes: A boom or a bust for society? In V.R. Baker (Ed.), *Rethinking the fabric of geology* (pp. 135-144). Geological Society of America, Special Paper 502.
[43] Preiser, R., Cilliers, P. & Human, O. (2013) Deconstruction and complexity: a critical economy. *South African Journal of Philosophy 32*(3), 261-273.
[44] Ripple, W.J., Wolf, C., Newsome, T.M., Galetti, M., Alamgir, M., Crist, E., Mahmoud, M.I., Laurence, W.F., and 15,364 scientist signatories from 184 countries (2017) World Scientists' Warning to Humanity: A Second Notice. *BioScience 67*(12), 1026-1028.
[45] Robinson, A. (2018) Did Einstein really say that? *Nature 557*, 30. *doi:* https://doi.org/10.1038/d41586-018-05004-4
[46] Rosen, D. (2016) Accessing creativity: Jungian night sea journeys, wandering minds, and chaos. *Nonlinear Dynamics, Psychology, and Life Sciences 20*(1), 117-139.
[47] Rosen, D. (2019) Being in uncertainties: An inquiry-based model leveraging complexity in teaching-learning. *Northeast Journal of Complex Systems 1*(1), article 5.
[48] Tufte, E. (1983) *Visual display of quantitative information*. Graphics Press.
[49] Tufte, E. (1990) *Envisioning information*. Graphics Press.
[50] Tufte, E. (1997) *Visual explanations*. Graphics Press.
[51] Tufte, E. (2006) *Beautiful evidence*. Graphics Press.
[52] Tukey, J.W. (1977) *Exploratory data analysis*. Addison-Wesley Publishing.
[53] Woermann, M. & Cilliers, P. (2012) The ethics of complexity and the complexity of ethics. *South African Journal of Philosophy 31*(2), 447-463.

Acknowledgments

The original manuscript was greatly improved by discussion and editorial input by Dr. LeeAnn Srogi and by three anonymous reviews.