INTRODUCTION TO COMPLEXITY SCIENCE

By Gene Soltero, CEO, Cimarron Capital, Inc.
Dallas, TX, September 2019

Little did I know when I wandered out from a cocktail reception to the veranda of a Miami hotel last December for some fresh air that I would meet someone who would introduce me to the specifics of a science I've seen all around me, but never really appreciated. There I met the CEO of a high-tech startup who told me they were using artificial intelligence, complexity science, type-2 fuzzy sets, natural language processing, and a bunch of other buzz-words to predict major changes in capital markets, *ahead of the crowd*, including the price of oil.

Now, I know a little bit about uncertainty in oil prices, having written a Master's thesis (*Decisions Under Uncertainty in International Petroleum Exploration*, 1966) under MIT's Morris Adelman (a world-renown petroleum economist) and having served as the petroleum economist for DeGolyer and MacNaughton (world-renown petroleum consultants). So, we got talking about the evolution of oil price prediction methods over the years, hitting the highlights of assessed probability distributions, behavioral psychology, econometric modeling, and mathematical solutions to non-linear three-dimensional supply and demand networks, and how all of these methods have been spectacularly unsuccessful in predicting the timing of oil price changes. We talked for hours (no kidding!) that evening and again by phone.

Within the next week, his chief scientific officer gave me a video chat presentation on the development of their model and how it comes up with probability distributions for near-term changes in the price of market variables (such as oil, gold, T-bills, $/EUR exchange rates) and occurrences of major market events (such as Fed policy changes, North Korean conflict, China economic crisis). Based upon my response to the presentation, my background in petroleum consulting, and more than 40 years in the C-suite of private and public oil companies, I was asked to join their panel of subject matter experts for the oil price prediction portion of their model. Being an engineer, I was curious as to the scientific basis for the model and how it works, so I started looking into complexity science (and all the other associated buzz-words).

After a couple months of research, I began to understand some of the breadth and rigor associated with complexity science and how this model could be economically useful to its target audience. I was soon invited to introduce the service to major oil companies and seek out partners to participate in field testing the oil price model. Because I hold several securities licenses, I was also invited to help the company complete its "B" round of startup financing. So, I began making introductions to oil companies and potential investors, mostly at the senior executive level, including those with robust data analytic departments.

I found that, like myself months ago, many senior executives have some knowledge of complexity science, but don't appreciate the extent that elements of complexity science have contributed to the development of all this high tech stuff around us....such as smart attendants (like Siri, Alexa and auto phone responders), terror attack prevention, hurricane forecasting (like those multiple tracks for Hurricane Dorian shown on TV), DNA testing, genetic modification, bullet trains, autonomous vehicles, high-end household appliances, new car electronics, data mining, cybersecurity, GPS directions, and even the software that stabilizes hand-held video camera recordings.

Continuing my research and education, I read several books (Appendix A), skimmed a few more (Appendix B), and plowed through (as best I could) a bunch of papers (Appendix C) on complexity science, mostly as it relates to the study of capital markets. I interviewed scientists in the field and had the opportunity to participate and observe while major portions of the model were tested and modified by the specialists. I also learned how Python works so I can demonstrate a simplified version of the model to others.

My purpose in writing this is to provide an introduction to complexity science for senior executives who don't have the time or inclination to make the detailed study I made, but who are in position to make decisions about having high tech specialists in their organizations do a deep dive on the model.

Complexity Science Overview

Several of the book and article writers refer back to Wikipedia and say it does a good job describing complexity science:

> *The term "complex adaptive systems," or "complexity science," is often used to describe the loosely organized academic field that has grown up around the study of complex adaptive systems. Complexity science is not a single theory—it encompasses more than one theoretical framework and is highly interdisciplinary, seeking the answers to some fundamental questions about living, adaptable, changeable systems.[1]...*
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> *Typical examples of complex adaptive systems include: climate; cities; firms; markets; governments; industries; ecosystems; social networks; power grids; animal swarms; traffic flows; social insect (e.g. ant) colonies; the brain and the immune system; the cell and the developing embryo; human social group-based endeavors, such as political parties, communities, geopolitical organizations, war, and terrorist networks. ...the internet and cyberspace—composed, collaborated, and managed by a complex mix of human–computer interactions.[2][3][4]*

A Google search for "complexity science" yields 2 million results. "Complex adaptive system" yields 500,000 additional results. A search of Google Scholar yields 114,000 books and articles, of which half have been written in the past twenty years and almost all of which have been written in the past forty years.

In the early 1990's there were 20 major institutions around the world with extensive background and research in complexity science.[5] Now there are hundreds. There are tens of thousands of practitioners working in industry and consulting firms providing complexity science solutions.

Brian Castellani, Professor of Sociology at UK's Durham University, is an expert in applying complexity science to social systems. He publishes a map of the *complexity sciences, a* screen

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[1] Holland John H. "Studying Complex Adaptive Systems". *Journal of Systems Science and Complexity*. (2006) (1): pp.1–8.

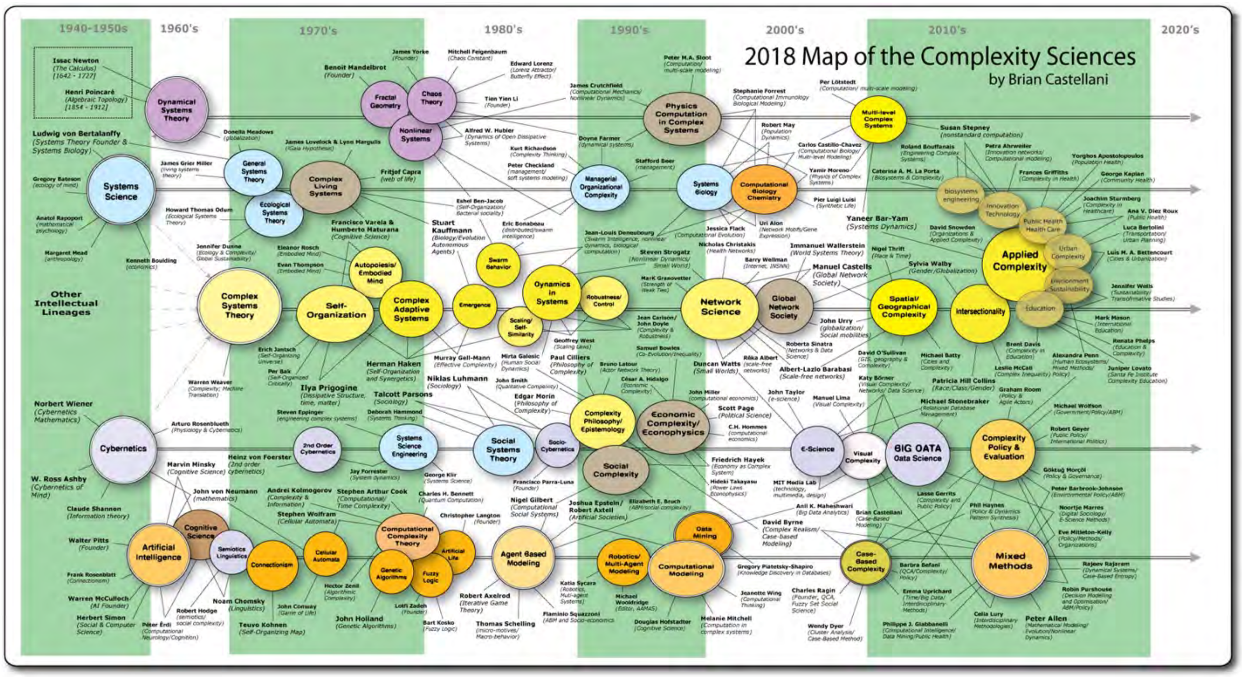
[2] Strogatz, Stephen H., Duncan J. Watts and Albert-László Barabási, explaining network theory and self-adaptation mechanism of complex systems in "Six Degrees of Separation*"*. BBC / Discovery. 2009. Accessed 15 August 2019.

[3] Andrus, D. Calvin. "Toward a Complex Adaptive Intelligence Community, The Wiki and the Blog". 2012. cia.gov. Accessed 15 August 2019.

[4] Subbarao, Alok. "The Internet Analyzed as a Complex Adaptive System." 2010. Accessed 15 August 2019.

[5] Gell-Mann, Murray. *The Quark and the Jaguar: Adventures in the Simple and the Complex.* New York: W. H. Freeman & Company, 1994. pp. xiv-xv.

shot of which is shown on the following page.(6) Clicking it links to the web page for the map that describes it in detail and provides further links to the background of each of its noted scholars who founded or exemplify the different areas of study and application. Although the map starts its time line in the 1940's, it provides links from Isaac Newton (1642-1727) and Henri Poincaré (1854-1912), particularly for the development of dynamical systems theory. Many other classical scientists also made contributions to the development of complexity science during their journeys, including Galileo, Maxwell, Boltzmann, Darwin, Mendel, Szilard, and Turing.(7)



The map is populated with 158 different scholars from the 1940's through current time. In the aggregate they have written more than 40,000 books and articles, which have been cited (according to Google Scholar) more than 5.4 million times. Of particular note is that 59 of the scholars (37%) have, at one time or another, been associated with the Santa Fe Institute (more about that later).

Castellani separates complexity science into the following major "intellectual traditions": dynamical systems, systems science, complex systems science, cybernetics, and artificial intelligence. A practicing complexity scientist with years of applications and consulting experience sees the intellectual traditions better described as nonlinear system dynamics, network science, rule-based systems, neural networks, fuzzy systems, and robotics & cybernetics.(8) There are others with different priorities, but they are all similar.

Milestones in Complexity Science

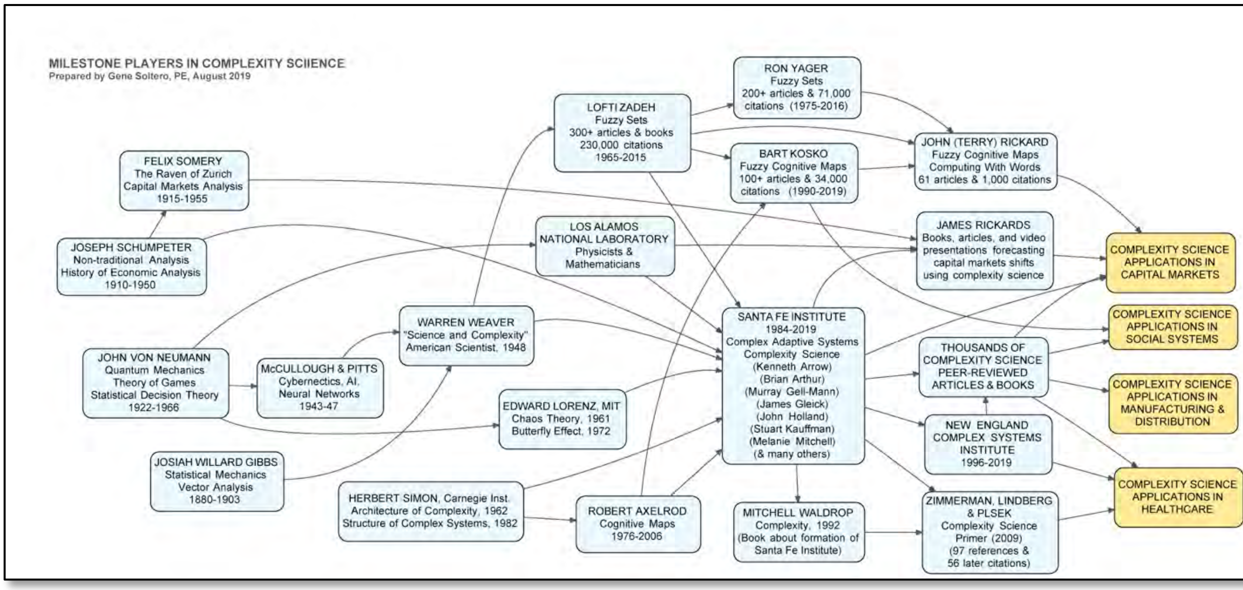
Prior to seeing the Castellani map, I had already put together my own simple map to help me piece together a reasonable depiction of the milestones in the development and applications of

6 Castellani, Brian. "Map of the Complexity Sciences." *Art & Science Factory.* (2018). https://www.art-sciencefactory.com/complexity-map_feb09.html

7 Mitchell, Melanie. *Complexity: A Guided Tour.* Oxford: Oxford University Press, 2009. 16-83.

8 John (Terry) Rickard. Email to author, July 2019.

complexity science, particularly as it might relate to models of the capital markets. Following the map are comments regarding highlights of a few of the key players instrumental in the origins and development of complexity science.



Joseph Schumpeter: My introduction to complexity science in capital markets started with books by Felix Somary[9] and James Rickards,[10][11][12] both writers who were directly or indirectly influenced by the early 1900's work of Joseph Schumpeter as described by Mark Perlman.[13] I also found numerous references to Schumpeter in the books and papers of the scholars of the Santa Fe Institute. I have a copy of Schumpeter's book, but have yet to plow through its 1300 pages. What I've learned, however, is that Schumpeter, up to his death in 1950, was an opponent of traditional equilibrium economics and an early proponent of dynamic analysis of economic systems, now called *complexity economics* by a number of scholars, including McKinsey & Company's Eric Beinhocker[14] and complexity science heavyweight W. Bryan Arthur.[15]

Warren Weaver's "Science and Complexity" is an 11-page paper published in 1948. Weaver sets out a scope of inquiry for the development of scientific methods using the skills of

[9] Somary, Felix. *The Raven of Zürich: The Memoirs of Felix Somary.* Translated from the German by A.J. Sherman. New York: St. Martin's Press, 1986.

[10] Rickards, James. *Currency Wars: The Making of the Next Global Crises.* New York: Portfolio/Penguin, 2011.

[11] Rickards, James. *The Death of Money: The Coming Collapse of the International Monetary System*. New York: Portfolio/Penguin, 2014.

[12] Rickards, James. *The Road to Ruin: The Global Elites' Plan for the next Financial Crisis*. New York: Portfolio/Penquin, 2016.

[13] Perlman, Mark. "Introduction" to Schumpeter, Joseph. *History of Economic Analysis.* London: Taylor & Francis, 2006.

[14] Beinhocker, Eric. *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*. Boston: Harvard Business School Press, 2006.

[15] Arthur, W. Brian. "Complexity Economics: A Different Framework for Economic Thought." *SFI Working Paper.* Santa Fe Institute, 2013.

mathematicians, physicists, and other scientists to investigate, understand and help solve the problems associated with the management of complex activities.[16]

Here's an introduction to Weaver's paper written by Rudolf Seising in 2011:

> *The mathematician Warren Weaver was an important science administrator during and after World War II. As the director of natural science of the Rockefeller Foundation he was significantly involved in changing the leading sciences from physics to life sciences. In his article "Science and Complexity" Weaver associates this change with the location of a "great middle region" of scientific problems of organized complexity" between the "problems of simplicity" that physical sciences are concerned with and the "problems of disorganized complexity" that can be solved by probability theory and statistics. Weaver stated that "something more is needed than the mathematics of averages." To solve such problems, he pinned his hope on the power of digital computers and on interdisciplinary collaborating "mixed teams". These quotations sound very similar to statements of Lotfi A. Zadeh's, when he founded his theory of "fuzzy sets" (in 1965).*

Edward Lorenz is described by Wikipedia as: "an American mathematician and meteorologist who established the theoretical basis of weather and climate predictability, as well as the basis for computer-aided atmospheric physics and meteorology. He is best known as the founder of modern chaos theory, a branch of mathematics focusing on the behavior of dynamical systems that are highly sensitive to initial conditions." He was awarded the 1991 Kyoto Prize for basic sciences in the field of earth and planetary sciences because he "profoundly influenced a wide range of basic sciences and brought about one of the most dramatic changes in mankind's view of nature since Sir Isaac Newton."

I read Lorenz's 1963 seminal paper on the subject, and could appreciate the significance of his conclusions, but not how he got there.[17] A number of primers or introductions to complexity science provide extended discussion of Lorenz and his importance. [18][19][20][21] But the best short form description comes from Wikipedia (again):

> *In 1953, Lorenz took over leadership of a project at MIT that ran complex simulations of weather models that he used to evaluate statistical forecasting techniques. By the late 1950s, Lorenz was skeptical of the appropriateness of the linear statistical models in meteorology, as most atmospheric phenomena involved in weather forecasting are non-linear... and discovered that small changes in initial conditions produced large changes in long-term outcome.*

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16 Weaver, Warren, "Science and Complexity", A*merican Scientist*, 36: 536 (1948). Based upon material presented in Chapter 1, *The Scientists Speak*. New York: Boni & Gaer Inc.,1947.

17 Lorenz, Edward. "Deterministic Nonperiodic Flow," *Journal of the Atmospheric Sciences* 20:130, 1963.

18 Waldrop, M. Mitchell. *Complexity: The Emerging Science at the Edge of Order and Chaos.* New York: Simon & Schuster, 1992.

19 Zimmerman, Brenda J., Curt Lindberg and Paul Plsek. "A Complexity Science Primer: What is Complexity Science and Why Should I Learn About It?" *NAPCRG Resources,* August, 2009. Adapted From: *Edgeware: Lessons From Complexity Science for Health Care Leaders*. Dallas: VHA Inc., 1998.

20 Mills, Alan. *Complexity Science: An Introduction (and Invitation) for Actuaries.* Society of Actuaries, 2010.

21 Frank, Jason. "Introduction to Complex Systems." *Course Outline.* Utrecht University, 2015

Lorenz's discovery, which gave its name to Lorenz attractors, showed that even detailed atmospheric modelling cannot, in general, make precise long-term weather predictions. His work on the topic culminated in the publication of his 1963 paper... and with it, the foundation of chaos theory....His description of the butterfly effect, the idea that small changes can have large consequences, followed in 1969.[22]

Lorenz's insights on deterministic chaos resonated widely starting in the 1970s and 80s, when it spurred new fields of study in virtually every branch of science, from biology to geology to physics. In meteorology, it led to the conclusion that it may be fundamentally impossible to predict weather beyond two or three weeks with a reasonable degree of accuracy. However, the recognition of chaos has led to improvements in weather forecasting, as now forecasters recognize that measurements are imperfect and thus run many simulations starting from slightly different conditions, called ensemble forecasting.

Of the seminal significance of Lorenz's work, Kerry Emanuel*, a prominent meteorologist and climate scientist at MIT, has stated: "By showing that certain deterministic systems have formal predictability limits, Ed put the last nail in the coffin of the Cartesian universe and fomented what some have called the third scientific revolution of the 20th century, following on the heels of relativity and quantum physics."*

Lotfi Zadeh was an MIT trained computer scientist and electrical engineer whose theories of "fuzzy logic" rippled across academia and industry, influencing everything from linguistics, economics and medicine to air-conditioners, vacuum cleaners and rice cookers.

Zadeh passed away in September 2017 at the age of 96. I am drawing liberally from a *New York Times* article that month to depict him and his contributions to complexity science.

Zadeh developed his "fuzzy logic," as a Berkeley professor of mathematics and computing. The concept, first set out in a 16-page paper in 1965, was an ambitious effort to close the gap between mathematics and the intuitive way that humans talk, think and interact with the world.[23]

If someone asks you to identify "a very tall man," for instance, you can easily do so — even if you are not given a specific height. Similarly, you can balance a broom handle on your finger without calculating how far it can lean in one direction without toppling over.

Professor Zadeh envisioned a mathematical framework that could mimic these human talents — that could deal with ambiguity and uncertainty in similar ways. Rather than creating strict boundaries for real world concepts, he made the boundaries "fuzzy." Something was not in or out, for example. It sat somewhere on the continuum between in and out, and at any given moment its location required application of a set of complex rules to define its position on the continuum. Zadeh developed the mathematics to govern those rules, using "membership functions" as substitutes for multi-dimensional probability distributions.

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[22] Lorenz, Edward. "Atmospheric Predictability as Revealed by Naturally Occurring Analogues". *Journal of the Atmospheric Sciences*. 26 (4): 636–646, 1969.
[23] Zadeh, Lotfi. "Fuzzy Sets." *Information and Control,* 8, 338-353 (1965).

In academic circles, Professor Zadeh's work was controversial and sometimes ridiculed, in part because it challenged other forms of mathematics and in part because of his terminology. "Fuzzy Logic" seemed to make fun of itself. But the logic itself was not fuzzy. It was a way of dealing with "fuzzy sets," collections of information whose boundaries were vague or imprecise. Over the years it proved to be an enormously influential idea that provided practical new ways to build consumer electronics, trade stocks, forecast weather and more.

Professor Zadeh originally envisioned fuzzy sets simply as a framework for harnessing language. But the idea expanded into other areas. It could provide a way for insurance companies to assess damage after an earthquake, for instance. Is the damage serious, moderate or minimal under company rules? Fuzzy sets could help.

The first significant real-life applications of fuzzy set theory appeared in the late seventies and early eighties. Among such applications were cement kilns and steel mill lines controlled by fuzzy logic. The first consumer product was Matsushita's shower head in 1986. Soon, many others followed, among them other home appliances, photographic equipment, and automobile transmissions. A major real-life application was the Tokyo underground train fuzzy logic control system (installed by Sendai) which began to operate in 1987 and was and is a striking success. In the realm of medical instrumentation, a notable real-life application is Omron's fuzzy- logic-based and widely used blood pressure meter.(24)

Since then, the theory was widely applied in many industrial applications, including medical diagnosis, NASA advanced piloting systems, consumer applications and autonomous vehicles navigation. Today the hype has faded, but fuzzy logic remains an active part of the mathematics that underpin the modern world. In the last twenty years, the development of natural language processors and artificial intelligence have relied heavily on Zadeh's mathematics.

In April 2013, Zadeh wrote:

...my 1965 paper on fuzzy sets was motivated by my feeling that the then existing theories provided no means of dealing with a pervasive aspect of reality—unsharpness (fuzziness) of class boundaries. Without such means, realistic models of human-centered and biological systems are hard to construct. My expectation was that fuzzy set theory would be welcomed by the scientific communities in these and related fields. Contrary to my expectation, in these fields, fuzzy set theory was met with skepticism and, in some instances, with hostility. What I did not anticipate was that, for many years after the debut of fuzzy set theory, its main applications would be in the realms of engineering systems and consumer products....

The past two decades have witnessed a significant change in the nature of applications of fuzzy logic. Non-engineering applications have grown in number, visibility, and importance. Among such applications are applications in medicine, social sciences, policy sciences, fraud detection systems, assessment of credit-worthiness systems, and economics.(25)

Scholarly publications evidence the magnitude of fuzzy logic and fuzzy sets in different applications and theoretical investigations. A search in August 2019 on Google Scholar shows

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[24] Zadeh, Lotfi. "Forward." *Advances in Fuzzy Systems.* Hindawi Publishing Company, 2013.
[25] Ibid.

1,030,000 documents for the query "fuzzy logic" and 604,000 documents for the query "fuzzy sets". Zadeh published more than 200 single-authored papers, and another 1000 collaborated papers, resulting in more than 230,000 citations.

Los Alamos National Laboratory was established in 1943 for the single purpose of designing and building an atomic bomb. Today its basic mission is maintaining the safety, security, and reliability of the nation's nuclear deterrent without the need to return to underground testing. it also works on nuclear nonproliferation and border security, energy and infrastructure security, and countermeasures to nuclear and biological terrorist threats.

During the 1950s and '60s the laboratory remained a prime designer of nuclear weapons. International disarmament and the arms-reduction treaties of the 1970's resulted in diminished demand for nuclear weapons production. The scientists there began looking at other areas of fundamental research that could benefit from the enormous computing power and advances in mathematics that had been developed by its nuclear physicists. Since its founding, the laboratory's scientists had been using non-linear mathematics to solve problems of high-energy particle physics, fluid dynamics, fusion reactions and thermonuclear blast waves.

The first areas of investigation for the technology transfer were molecular biology and computer simulations of weather and other chaotic events coming from the Lorenz research. By the mid 70's the laboratory had scientists from a number of different disciplines working on solutions to complex problems. The result, with the enthusiastic support of the Los Alamos theory group, was a vigorous program for non-linear science within the theory division, and eventually a Center for Nonlinear Systems operating entirely on its own.

In 1982, George Cowan, the laboratory's head of research, accepted a seat on the White House Science Council. Their meetings furthered his interest in encouraging scientific investigation of complex systems for policy making purposes and reinforced ideas he had been developing for a new complexity research institute separate from the laboratory, but close enough to make use of its scientists and computing power. In 1983, with support from the White House Science Council, Cowan put together a team of senior fellows from the laboratory and "A-List" super scientists from other institutions, including Nobel Prize winners Murray Gell-Mann and Phil Anderson, to organize the new institute. The laboratory continued its research in classic science, remaining the chief U.S. nuclear weapons laboratory, but also becoming one of the largest scientific research sites in the world.

Santa Fe Institute, located 30 miles from Los Alamos, was founded in 1984. The senior fellows from Los Alamos and the key outsiders sought to create an institution that would be interdisciplinary in nature and make use of non-linear dynamics and computer modeling. The institution would favor synthetic efforts over specialization, de-emphasize disciplinary boundaries and bureaucracy, and be a haven for scientists in search of a broader view of their enterprise. There are numerous accounts of its origins and early years. [(26)(27)(28)(29)] The SFI website carries two such accounts.[(30)] I like Dillon's historical summary below, written in 2001.[(31)]

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26 Waldrop (1992).
27 Gell-Mann (1994).
28 Beinhocker (2006).
29 Mitchell (2009).
30 https://www.santafe.edu/about/history
31 Dillon, Dan. "Review of the Santa Fe Institute: Institutional and individual qualities of expert interdisciplinary work," *Harvard Interdisciplinary Studies Project*. Cambridge: Harvard University, 2001.

...the fellows held a pair of small conferences just as the institution was beginning to take shape. Renowned scientists from several disciplines attended, and many put forth their own ideas for the proposed institution. As the scientists spoke, Cowan, Gell-Mann, and the other fellows from Los Alamos detected a repeating theme: several of the researchers focused on how simple elements gave rise to complex phenomena, phenomena whose qualities could not easily be predicted from the nature of the constituent elements. The group from Los Alamos decided that their new institution would focus on "complexity," a term whose exact meaning was purposely left unclear: the founders wanted a wide range of scientific subjects to fit within the institute's purview.

By 1987, after some early bumps and bruises with respect to funding, space, and organizational infrastructure, the Santa Fe Institute was firmly established in an old Santa Fe building that had previously been a convent. Small in size, SFI was designed as a visiting institution, and the few residential faculty members were greeted regularly by researchers from other institutions who came to work for short periods of time (ranging in duration from a day to a few years).

Crucially, a few of the early workshops held at the Santa Fe Institute were quite successful. Particularly notable was a series of sessions that brought economists (including Nobel laureate Kenneth Arrow) into contact with physical scientists. Stimulated by Citicorp CEO (and early SFI funder) John Reed's sense that the new institution's work might help produce a better understanding of the world's economy, a number of prominent economists traveled to the young Institute and shared their work. Almost every time an economist finished his or her presentation, the physicists in the audience let loose a barrage of questions and critiques concerning (among other things) the economists' somewhat extreme devotion to mathematical models and the notion of economic equilibrium. The ensuing exchanges were worthwhile (if not painless) for both groups: the economists were forced to reevaluate their basic assumptions and methodologies, while the physicists were exposed to questions and issues that resided far outside their domain. Both groups realized that working together might prove fruitful, and in the late 1980s, several collaborations between economists and physicists associated with the Santa Fe Institute took place.

Those collaborations have had an impact both on how economics is done and on possible career paths for physicists. They helped to legitimate the Santa Fe Institute and also served to create a stir in the intellectual community. The Institute's members did not try to divert this attention; as one subject told us, it is important to create a "fad" when you are trying to get a new enterprise off the ground. By the late 1980s, the Institute had begun to earn recognition as the nation's leader in the study of complexity and one of its foremost interdisciplinary institutions...

With respect to creativity, I view the Santa Fe Institute as roughly equal parts Freud and Einstein. SFI researchers work on topics, like robustness, which are not systematically studied elsewhere, using methods and tools (loosely organized under the heading of "complexity science") that are still rather unusual, despite their growing popularity.

Certainly, SFI is a pioneer with respect to complexity science in the United States, and the Institute as a whole can be seen as an important experiment in how science is done. However, most of the projects worked on at the Santa Fe Institute have clear ties to

> *existing disciplines. While this in no way minimizes the creative acts required to formulate and work through these projects, they differ from efforts that are completely radical in their formulation.*
>
> *Perhaps the Santa Fe Institute can best be seen as in balance between two poles: one being a completely wild, radical approach to science, and the other being the most conservative approach possible. By combining aspects of both poles and therefore staying somewhere in the middle, the Santa Fe Institute has managed to carry out important work and thrive institutionally for the past 17 years.*

In the 18 years since Dillon's study, SFI has clearly established itself as an international focal point for complexity science solutions of real-world problems. Its 59 scientists shown on the Castellani map have published more than 14,000 articles and books that have been cited more than 1.8 million times by others in the field. Its website[32] contains up to date extensive content about complexity science applications, as well as considerable educational resources; and it is the perfect place for anyone reading this memo to learn more about complexity science.

Another website resource is the outline of a current course in complexity science at Olin College. It contains student reviews of different chapters of thirty key non-technical books on the subject (including some referred to in this paper).[33]

Oil Price Model

In order to advance beyond econometric modeling for oil price prediction[34] our client used several complexity science concepts to design the oil price model, and its sister models to predict, *ahead of the crowd*, major changes in capital markets. Using behavioral science and neural network analysis, the scientists worked with subject matter experts to design a fuzzy cognitive map[35] incorporating the forty most important factors affecting oil price changes. They identified the relationships among the factors as linked nodes on a single map, laying out the direction and strengths of those relationships in membership functions similar to probability distributions. Initial value ranges and membership functions for those value ranges were established by the scientists using input from the subject matter experts.

The value and relationship strength membership functions are represented by fuzzy sets that are combined mathematically in a proprietary core analytic engine to yield probability distributions for the direction and magnitude of possible changes in oil prices in the upcoming three to six-month period. Changes to the membership functions come on a real time basis through three separate routes, and the model is continuously and dynamically updated as those changes come in, so that analysts using the model can see how the forward probability distribution changes over time.

Some of the node membership functions change due to algorithms fed by real-time data streams from international market sources for thousands of commodities subsets, financial products and financial indicators. Some of them change due to algorithms fed by real-time

32 https://www.santafe.edu
33 https://sites.google.com/site/compmodolin
34 Frey, Giliola, Matteo Maneral, Anil Markandya and Elisa Scarpa. "Oil Price Forecasting: A Critical Survey." *CESifo Forum.* January 2009.
35 Aguilar, Jose. "A Survey about Fuzzy Cognitive Maps Papers (Invited Paper)." *International Journal of Computational Cognition.* June 2005

natural language processors from the hundreds of thousands of documents published every day around the world. Some are changed by both market forces and natural language processor results. A few of the nodes are directly changed by results from sister models, of which there are currently six in operation and another seven in development.

Summary

Accurate oil price prediction has long been a challenge due to the nature of commodity supply and demand behavior, complexity of dominant variables, interdependencies that arise from human reactions, and cause and effect cascades that can move markets dramatically at each new piece of information. The science of complex adaptive systems uses many of the tools of several fields of classical science, including economics, behavioral science, system dynamics, and statistical analysis, combined in new and more powerful solutions, to solve this and other problems previously thought to be unsolvable. Advances in computing power and new techniques are enhancing the solution process, allowing more variables to be mapped, more scenarios to be tested and validated on historical data, and faster response to new information.

APPENDIX A
COMPLEXITY SCIENCE BOOKS TO READ

Alberts, David S. and Thomas J. Czerwinski, Editors. *Complexity, Global Politics and National Security.* Washington: National Defense University, 1997.

Beinhocker, Eric. *The Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics*. Boston: Harvard Business School Press, 2006.

Gell-Mann, Murray. *The Quark and the Jaguar: Adventures in the Simple and the Complex.* New York: W. H. Freeman & Company, 1994.

Mills, Alan. *Complexity Science: An Introduction (and Invitation) for Actuaries.* Society of Actuaries, 2010.

Mitchell, Melanie. *Complexity: A Guided Tour.* Oxford: Oxford University Press, 2009.

Somary, Felix. *The Raven of Zürich: The Memoirs of Felix Somary.* Translated from the German by A.J. Sherman. New York: St. Martin's Press, 1986.

Rickards, James. *Currency Wars: The Making of the Next Global Crises.* New York: Portfolio/Penguin, 2011.

Rickards, James. *The Death of Money: The Coming Collapse of the International Monetary System*. New York: Portfolio/Penguin, 2014.

Rickards, James. *The Road to Ruin: The Global Elites' Plan for the next Financial Crisis*. New York: Portfolio/Penguin, 2016.

Waldrop, M. Mitchell. *Complexity: The Emerging Science at the Edge of Order and Chaos.* New York: Simon & Schuster, 1992.

APPENDIX B
COMPLEXITY SCIENCE BOOKS TO SKIM

Arthur, W. Brian. *Complexity and the Economy.* Oxford: Oxford University Press, 2015.

Castellani, Brian and Frederic Hafferty. *Sociology and Complexity Science: A New Field of Inquiry.* Springer International Publishing AG, 2009.

Casti, John. *Paradigms Lost: Tackling the Unanswered Mysteries of Modern Science.* New York: Simon and Shuster, 1989.

Dolphin, Tony and David Nash, Editors. *Complex New World: Translating New Economic Thinking into Public Policy.* London: Institute for Public Policy Research, 2012.

Downey, Allen B. *Think Complexity.* Needham, MA: Green Tea Press, 2016.

Gleick, James. *Chaos: Making a New Science.* New York: Penguin Books, 1988.

Landreth, Harry and David C. Colander. *History of Economic Thought.* Boston: Houghton, Mifflin Company, 2001.

Holland, John H. *Emergence: From Chaos to Order.* Oxford: Oxford University Press, 1998.

Simon, Herbert A. *The Sciences of the Artificial.* Cambridge: The MIT Press, 1996.

Wolfram, Stephen. *A New Kind of Science.* Wolfram Media, Inc., 2002.

Zimmerman, Brenda J., Curt Lindberg and Paul Plsek. *Edgeware: Lessons From Complexity Science for Health Care Leaders.* Dallas: VHA, Inc., 1998.

APPENDIX C
COMPLEXITY SCIENCE ARTICLES AND OTHER RESOURCES

Abraham, Ralph H. "The Genesis of Complexity." *Advances in Systems Theory, Complexity, and the Human Sciences.* 2002.

Aguilar, Jose. "A Survey about Fuzzy Cognitive Maps Papers (Invited Paper)." *International Journal of Computational Cognition.* June 2005.

Andersson, Claes. "History of Complexity Science." Chalmers University of Technology. 2018. Accessed 22 July 2019.

Andrus, D. Calvin. "Toward a Complex Adaptive Intelligence Community, The Wiki and the Blog". 2012. cia.gov. Accessed 15 August 2019.

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