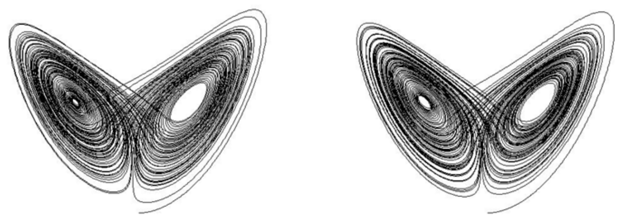
A simple qualitative, yet mathematical model powerfully illustrates how breakthrough innovators come to know

Flatland: The non-linear nature of breakthrough innovation

Breakthrough innovators are well-described as mathematically chaotic individuals

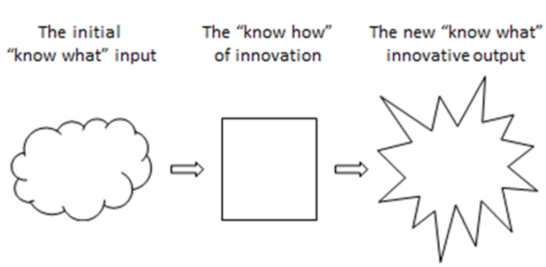


In the Essay 20 (*Flatland: A glimpse of things to come*) we embarked on a journey, one that eventually will propel us into new dimensions of insight. Beginning with the simple framework depicted in Figure 1, we noted that a breakthrough innovator's "know what" base of factual information serves as the input to their "know how" of innovation skill, with the result being abrupt or emergent innovative insight, a new "know what" output. Dissecting this model, we developed its "know what" aspects in Essays 21 and 22. In the present essay, we next will explore the "know how" of innovation.

The "know how" of innovation

While seeking to discern or impose order in or on it, industrial practitioners and academic researchers agree that breakthrough innovation is a messy, complex process that does not follow neatly-defined paths. While a finite set of certain activities must be conducted as the innovation process unfolds (such as identifying the best problem to address, understanding the problem deeply, and synthesizing what is known into an innovative product concept), these activities typically are attended to repeatedly, in only a general order initially and with little or no predictability thereafter.[i] Illustrating the iterative, feedback-laden nature of innovation, those describing it at times speak of "ruminating" or "chewing on" ideas as they emerge into conscious awareness. The use of analogous language from meteorology also sheds light on innovation; in an effort to stimulate highly-creative, innovative output, no holds barred "brainstorming" is often employed.

A very simple model of the epistemology of breakthrough innovation **1**



The non-linear nature of breakthrough innovators

Taken individually and collectively, the characteristics that describe the epistemological elements of innovation (outlined herein and in Essay 21: unpredictability, abruptness of or emergent change in behavior, feedback, iteration, and extreme sensitivity to slight differences) suggest that a non-linear process is present and, thus, that the underlying nature of innovative discovery can be described mathematically by using chaos theory.[ii]

A non-linear system is one whose mathematical description expresses relationships that are not strictly proportional.[iii] Mathematically, non-linear relationships occur variously, such as: power law (e.g. $y = x^2$, $y = x^{1.7}$, etc.), trigonometric (e.g. $y = \sin(x)$), or logarithmic (e.g. $y = \log(x)$). When non-linear terms do not exist, an equation can be broken down into smaller parts that can be analyzed separately, making an analytical solution possible, something impossible for a non-linear system.[iii] As a result of these mathematical differences, there exists a striking difference between the behavior and characteristics of the mathematical solutions of linear and non-linear systems. Some of the most salient of these differences are summarized in Table I.[ii, iii]

Non-linear systems abound in nature, ranging from those in weather (e.g. storms), geology (e.g. earthquakes) and sound (e.g. the overtones of a piano). Non-linear systems also play a key role in engineered systems, such as the conversion of an audible signal to a much higher ≫

LINEAR SYSTEMS	NON-LINEAR SYSTEMS
Gradual changes in behavior	Extreme changes in behavior occur abruptly and without warning
Modest sensitivity of output to initial conditions	Extreme sensitivity of output to initial conditions
Behavior is both deterministic and predictable	Behavior is deterministic, but not predictable
Study of linear systems is "Classical"	Study of non-linear systems is known as "Chaos theory"

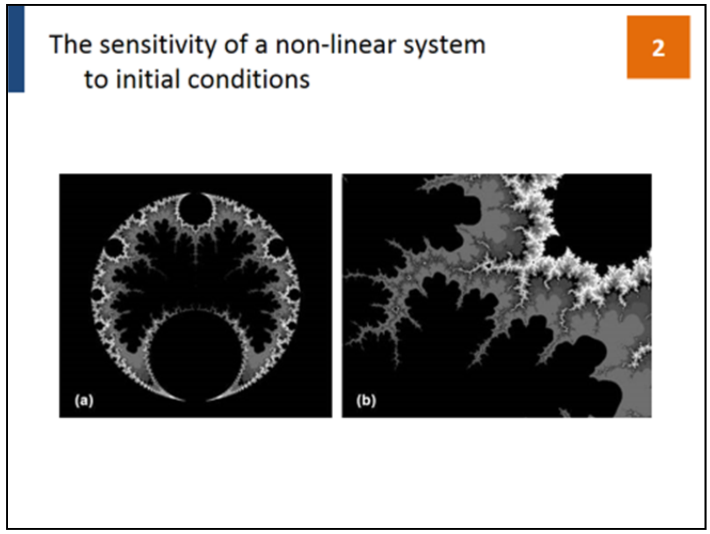
Table I: Comparison of linear and non-linear systems frequency, enabling its transmission in a communication system.

Perhaps the best-known characteristic of non-linear systems is the so-called "Butterfly Effect," which alludes to a system's extreme sensitivity to initial conditions. The name "Butterfly Effect" arose from, and is illustrated by, the observation that "the flap of a butterfly's wings in Brazil can set off a tornado in Texas" – that is, that an ever so slight disturbance in one part of the world can yield extreme consequences for the weather experienced in a distant land. A more familiar illustration of the "Butterfly Effect" is the proverb "For the want of a nail," where the lack of just one nail carries with it unfortunate, profound consequences:[iii]

> For want of a nail the shoe was lost.
> For want of a shoe the horse was lost.
> For want of a horse the rider was lost.
> For want of a rider the battle was lost.
> For want of a battle the kingdom was lost.
> And all for the want of a horseshoe nail.

The "Butterfly Effect" can be visualized graphically by viewing the familiar, striking images of fractals – such as those of the well-known Mandelbrot Set – images that are literally maps of the solutions to a non-linear equation. The color or shading of a given point in such a map (each point represents a distinct initial condition) represents the rate at which the iterated output of the non-linear function approaches infinity. This is illustrated in Figure 2 (2b represents a 100x magnification of 2a).[iv] That adjacent points in this image can exhibit such a striking contrast of shading is an illustration of how sensitive non-linear systems are to very slight differences in initial conditions. That the same sensitivity is observed at ever increasing magnification also is characteristic of non-linear systems.

This is observed as well in the nearly identical "Lorenz attractor" images (in this essay's header) depicting the physical trajectory of a non-linear system. That they are similar but not identical (due only to their slightly different initial conditions) and that breakthrough innovation exhibits the identical extreme sensitivity to initial conditions, as well as the other characteristics of non-linear systems listed in Table I, provides significant substantiation that it is, in fact, a non-linear process. ■



Bruce A. Vojak is Associate Dean for Administration and an Adjunct Professor in the College of Engineering at the University of Illinois at Urbana-Champaign. Prior to joining the university in 1999 he was Director of Advanced Technology for Motorola's non-semiconductor components business; earlier he held business development and research positions at Amoco and a research position at MIT Lincoln Laboratory. In addition to his administrative responsibilities, he teaches and conducts research on the topics of innovation and strategic technology management. With Abbie Griffin and Ray Price he is co-author of Serial Innovators: How Individuals Create and Deliver Breakthrough Innovations in Mature Firms (Palo Alto: Stanford University Press, 2012). Further, he currently serves on the Board of Directors of Midtronics, Inc. and the Advisory Board of JVA Partners, as well as periodically consulting for Procter & Gamble. Bruce holds B.S., M.S. and Ph.D. degrees in Electrical Engineering from the University of Illinois at Urbana-Champaign and an MBA, with concentrations in finance and marketing, from the University of Chicago's Booth School of Business.

This essay is based on a portion of chapter 24 (*On the Epistemology of Breakthrough Innovation: The Orthogonal and Non-Linear Natures of Discovery* by Bruce A. Vojak and Raymond L. Price) of Philosophy and Engineering: Reflections on Practice, Principles and Process, Diane Michelfelder, Natasha McCarthy, David Goldberg (editors) (New York: Springer, 2013).

[i] Bruce A. Vojak, Raymond L. Price, and Abbie Griffin, *Corporate Innovation*, in the Oxford Handbook of Interdisciplinarity, Robert Frodeman, Julie Thompson Klein and Carl Mitcham (editors) (Oxford, UK: Oxford University Press, 2010).

[ii] Steven Strogatz, Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering (Boulder, CO: Westview Press, 2001).

[iii] James Gleick, Chaos: Making a New Science (New York: Viking Penguin, 1987).

[iv] Many thanks to Alfred Hübler for permission to use his Lorenz attractor images (header) and to Scott Burns (Design by Algorithm; http://www.designbyalgorithm.com) for permission to use his Mandelbrot images (Figure 2).

"On the Epistemology of Innovation: How Breakthrough Innovators Connect the Dots" is a series of brief, occasional essays addressed to executives, managers, and technologists responsible for innovation in industry. Its purpose is to challenge readers to reflect broadly and deeply on the practice of innovation – in particular on how innovators come to know what to do today – in order to succeed commercially in the future. Essays are available without charge at the University of Illinois' digital archive at https://www.ideals.illinois.edu/handle/2142/27667. The discussion group at http://epistemology-of-innovation.com is a place to provide feedback and dialog with the author and others regarding these essays, as well as to register to receive notice of new essays as they are issued.