PHILOSOPHY OF SCIENCE

The Cha-Cha-Cha Theory of Scientific Discovery

Dividing the discovery process into three categories can aid in understanding the genesis of small, everyday advances as well as breakthroughs that appear in history books.

Daniel E. Koshland Jr.

Scientific discoveries are the steps—some small, some big—on the staircase called progress, which has led to a better life for the citizens of the world. Each scientific discovery is made possible by the arrangement of neurons in the brain of one individual and as such is idiosyncratic. In looking back on centuries of scientific discoveries, however, a pattern emerges which suggests that they fall into three categories—Charge, Challenge, and Chance—that combine into a "Cha-Cha-Cha" Theory of Scientific Discovery. (Nonscientific discoveries can be categorized similarly.)

"Charge" discoveries solve problems that are quite obvious—cure heart disease, understand the movement of stars in the sky—but in which the way to solve the problem is not so clear. In these, the scientist is called on, as Nobel laureate Albert Szent-Györgyi put it, "to see what everyone else has seen and think what no one else has thought before." Thus, the movement of stars in the sky and the fall of an apple from a tree were apparent to everyone, but Isaac Newton came up with the concept of gravity to explain it all in one great theory.

"Challenge" discoveries are a response to an accumulation of facts or concepts that are unexplained by or incongruous with scientific theories of the time. The discoverer perceives that a new concept or a new theory is required to pull all the phenomena into one coherent whole. Sometimes the discoverer sees the anomalies and also provides the solution. Sometimes many people perceive the anomalies, but they wait for the discoverer to provide a new concept. Those individuals, whom we might call "uncoverers," contribute greatly to science, but it is the individual who proposes the idea explaining all of the anomalies who deserves to be called a discoverer.

"Chance" discoveries are those that are often called serendipitous and which Louis Pasteur felt favored "the prepared mind." In this category are the instances of a chance event that the ready mind recognizes as important and then explains to other scientists. This category not only would include Pasteur's discovery of optical activity (D and L isomers), but also W. C. Roentgen's x-rays and Roy Plunkett's Teflon. These scientists saw what no one else had seen or reported and were able to realize its importance.

There are well-known examples in each one of the Cha-Cha-Cha categories (see the figure). Two conclusions are immediately apparent. The first is that the original contribution of the discoverer can be applied at different points in the solution of a problem. In the Charge category, originality lies in the devising of a solution, not in the perception of the problem. In the Challenge category, the originality is in perceiving the anomalies and their importance and devising a new concept that explains them. In the Chance category,

CATEGORIES OF DISCOVERY

Problem that needed solving	Discovery	Discoverer	Category of discovery
Movement of stars, Earth, and Sun	Gravity	Newton	Charge
Structure of C_6H_6	Benzene structure	Kekulé	Challenge
Clear spots on petri dish	Penicillin	Fleming	Chance
Constant speed of light	Special relativity	Einstein	Challenge
Preventing heart attacks	Cholesterol metabolism	Brown & Goldstein	Charge
Crystals of D- and -L tartaric acid	Optical activity	Pasteur	Chance
Atomic spectra that could not be explained	Quantum mechanical atom	Bohr	Challenge
How DNA replicates and passes on coding	Base pairing in double helix	Watson & Crick	Challenge
Reagent "stuck" in storage cylinder	Teflon	Plunkett	Chance
Why offspring look like their parents	Laws of heredity	Mendel	Charge

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D. E. Koshland Jr. passed away on 23 July 2007. He was a professor of biochemistry and molecular and cell biology at the University of California, Berkeley, since 1965. He served as *Science*'s editor-in-chief from 1985 to 1995.

the original contribution is the perception of the importance of the accident and articulating the phenomenon on which it throws light.

Second, most important discoveries are usually not solved in one "Eureka" moment, as movie scripts sometimes suggest. True, there are moments in which a scientist has been mulling over various facts and problems and suddenly puts them all together, but most major discoveries require scientists to make not one but a number of original discoveries and to persist in pursuing them until a discovery is complete. Thus, to solidify his theory of gravity, Newton developed calculus and laws of physics that he described in his *Principia*. In a modern example, Michael Brown and Joseph Goldstein not only studied the metabolism of cholesterol but also discovered the role of lipoprotein receptors and the movement of key proteins from the outside to the interior of cells. Great discoveries are frequently covered in textbooks with a single word or phrase, but the concepts actually become solidified as scientific understanding by a series of discoveries.

It is also pertinent to define "the prepared mind" that is required for all of these innovations. Such a mind must be curious and knowledgeable. Curious refers to the fact that the individual is interested in phenomena and is constantly seeking to understand and explain them. Knowledgeable means that the individual has a background of facts and theories as a fertile incubator into which the new facts can fall.

The Cha-Cha-Cha Theory pertains to small everyday findings by scientists as well as the big discoveries that appear in history books. When, for example, a researcher discovers a new chemical isolated from a plant, there is so much understood today that the "charge" to that scientist is to find the formula and structure of the compound. There are now many ways to find the structure of an unknown chemical. Along the way there may be anomalous results that present challenges to the scientist and unexpected findings that must be interpreted by the prepared mind. So each of these represent real discoveries, not as big as a theory of gravity, but important just the same.

Finally, scientific discoveries are not that different from nonscientific discoveries. In the earliest days, there was an obvious "charge" for a set of rules to guide conduct in the close environment of a village that led to social customs and religious guidelines such as the Ten Commandments. As more complex societies emerged, the idea of a democratic vote probably resulted from a "charge" that saw the importance of getting consensus. The Magna Carta and the Bill of Rights came out of "challenges" to an entrenched social system. So when Einstein said that scientific thinking and general thinking were not that different, he probably meant that the patterns of thought of those with "prepared minds" in government and law operated by some of the same general principles as science, even though the methods of science and law are very different.

Someday we may understand the arrangement of neurons in the brain enough to understand how originality can arise. A wild guess would be that the brain of a discoverer has a greater tendency than the average individual to relate facts from highly separate compartments of the brain to each other. As a step to making that Herculean problem tractable, we can at least follow the traditions of scientific reductionism and use the Charge, Challenge, and Chance categories to make the interpretation of brain imaging experiments easier to analyze.

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APPLIED PHYSICS

How to Strum a Nanobar

Miles Blencowe

A method for vibrating a nanocantilever may yield much more sensitive measurement tools and computers based on mechanical logic devices.

Nanotechnologists are increasingly interested in using mechanical vibrating structures as fast, sensitive detectors of such properties as electric charge (*1*), magnetism (*2*), and mass (*3*). These devices make good detectors because, just as a bit of sealing wax changes the frequency of a tuning fork, the properties of a nanoresonator will change in response to external forces. Nanomechanical resonators may also be suitable as ultracompact, high-frequency filters and mixers for electromagnetic signals (*4*). That is, by tailoring the vibrational properties of the structure, only select frequencies are detected. For these applications to be feasible, it is crucial that we have the ability to drive the nanomechanical resonator into motion with an electromagnetic force (i.e., "actuate" the resonator) in an efficient and controllable way. At the same time, the delicate quivering of a nanomechanical resonator as it responds to a local stimulus must be efficiently transduced into an electromagnetic signal that can be amplified to measurable levels. These requirements of efficiency, compactness, and speed favor methods of actuation and transduction that are part of the nanomechanical resonator itself.

On page 780 of this issue (*5*), Masmanidis *et al.* demonstrate an intrinsic actuation method ideally suited to nanoscale mechanical resonators. The method relies on a property of some crystals called piezoelectricity (*6*), deriving from the Greek *piezen*, meaning "to press." As the name suggests, stressing such a crystal will produce a corresponding voltage between certain faces of the crystal. Conversely, applying a voltage between the same faces will generate a corresponding mechanical deformation or strain of the crystal. Masmanidis *et al.* use both singly clamped cantilevers and doubly clamped bridge resonators (see the micrograph) that are fashioned from gallium arsenide (GaAs) (*7*). The underlying GaAs crystal orientation is chosen such that applying a voltage between the top and bottom faces will cause it to either elongate or shorten, depending on the polarity of the applied electric field.

To understand better how the motion is produced, consider a GaAs cantilever and suppose that an ac voltage source is applied between its top and bottom faces. If the frequency of the ac voltage matches that of one of the cantilever's longitudinal vibration modes (i.e., stretching modes along the direction of the cantilever), then the cantilever will ring at this frequency. However, longitudinal modes are difficult to detect because of their relatively high frequencies and small displacement amplitudes. As with stringed musical instruments, it is preferable to excite the lower frequency, bending modes of the cantilever, especially the fundamental mode. The method of actuation should also be internal to the cantilever and not require external electrodes attached to its top and bottom faces.

Masmanidis *et al.* elegantly meet both of

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