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How Scientists Reason

Plato began with a universal "idea of the good" and worked down from there. Galileo reversed the process, starting with first-hand experience and working up. The famous experiments in which he dropped shot of assorted sizes from the Leaning Tower of Pisa, timing their fall, proved that the velocity of freely falling bodies does not depend on weight. He went on to inquire what it does depend on, which meant more experiments, and the invention of instruments for closer observation.

Galileo sought the facts and used his powerful reason on them. The Schoolmen began and ended with reason. Reason told them that heavy bodies should fall faster than lighter bodies, and they could not be bothered with hauling shot to the tops of towers. Along about A.D. 1400, facts began to receive the right of way in Western thought, and gradually the great era of modern science opened, the era we are now in up to our necks.

No single cause can be found for the change. A complex process seems to have been at work. The Crusades helped to free communication lines, over which flowed the mathematics and the scientific observations of the Arab world. Freer communication encouraged freer thinking. Marco Polo made his way to China, the Portuguese pushed down the west coast of Africa, Columbus landed in the West Indies. The explorers and navigators needed instruments to steer by, and methods for calculating longitude and latitude. Trade followed exploration, with new products and a growing curiosity about the world.

The new knowledge was bitterly resisted in many quarters. Bruno was burned at the stake for dangerous thoughts about religion, and other pioneers, including Galileo himself, were roughly handled. But by 1600 it was safe to investigate the solar system and most material things, as well as energy and motion. The applications of science in navigation, trade, mining, manufactures, were far too valuable to be throttled by syllogisms. Presently Newton arrived at the principles of gravitation, perhaps the greatest synthesis of observation, reason, and verification ever achieved by one human mind.

The exciting story of the rise of science has often been told, and I will not repeat it here. It is symbolized by Galileo. Instead of merely thinking about falling bodies, he went out and dropped some.

The three steps in the scientific method follow naturally: *First*, get together the facts bearing on your question. *Second*, develop a theory, or hypothesis, to explain the facts. *Third*, arrange experiments to verify the hypothesis. Arrange them in such a manner that other competent observers can repeat them. Maintain a healthy skepticism throughout, and be ready to say "I was wrong."

The growth of science in the last four hundred years has been aided by a number of basic concepts and mental tools, largely unknown or ignored in the logic of the ancients. Journeymen thinkers, such as you and I, can take advantage of them, where the journeyman thinker before Galileo had no such opportunity. He had to stick to common sense, or go in for the rigors of the syllogism. You and I, lacking a Ph.D. in physics, may not be able to follow the logic of science all out, but we can use the general approach. We can ask what are the facts, and has the theory been verified? We can keep an open mind until competent observers reach some kind of agreement. We can avoid pounding on the table on matters we know little about. Was it Bertrand Russell who said that one's certainty varies inversely with one's knowledge?

To refresh the reader's memory, here is a brief sketch of some of the chief mental tools of modern science, which, consciously or unconsciously, are part of the background of everyone who tries to think rationally today.

PROBABILITIES INSTEAD OF ABSOLUTES

Scientists have become very shy of declaring a thing 100 percent so, though they may settle sometimes for 99.999 percent. The hope is to make a closer and closer fit to nature. Thus Newton greatly refined our knowledge with his laws of gravitation. Einstein corrected Newton in some particulars with the laws of relativity, and made a still closer fit. Physicists today are tightening some of Einstein's concepts, with a big change foreseeable if quantum theory can be reconciled with relativity. Modern scientists find probabilities not only more accurate but more fruitful in the pursuit of knowledge.

This is particularly true in social science, where probabilities are usually lower than in physics. The social and political problems which we argue about lie in this area, and to take a 100 percent position usually ends intelligent discussion. One had better not say: "Russia is going to collapse within six months," but rather: "If the reports on the crisis in Russian agriculture are true, it looks as thought the Kremlin would have to change its foreign policy."

Or take the aptitude testing for airline pilots. The absolutist position would be that a man is a good pilot or he isn't. Social scientists during the war worked out tests for a series of psychological and physical traits. They probed by controlled experiments that a candidate who ranked high in the tests had about an 80 percent chance of making good on the flying field -- not that the tests were infallible or perfectly correlated with performance but that the *probability* was high. With tens of thousands of young men taking the test, the savings in human life, to say nothing of the taxpayer's money, were of course enormous.

MATHEMATICAL THINKING

This concept of probability, which revolutionized science, originated in repeated throws of dice, with a careful scoring of results. Upon these results the probability mathematics of Pascal and Fermat was reared. No earlier civilization had had more than the rudiments of the mathematics to aid in the pursuit of knowledge. Even the available number systems put a powerful brake on figuring things out. Pity the Roman civil engineer who, to compute his cuts and fills, had to multiply XLVIII by CCCXXIV.

Ever since the Arabs introduced the decimal system mot Europe, mathematics has been expanding. Newton, before he could explain to himself or others what he had found, had to invent integral calculus. Einstein, of course, did much of his thinking in the language of mathematics. The gravitational equations in his general theory of relativity are written in a form of mathematics called *tensors*. Meanwhile, George Boole in the nineteenth century invented a new kind of algebra which applied not to numbers but to relations. It is useful both to students of logic and to telephone company engineers planning to expand the dial system.

In modern symbolic logic, instead of manipulating words, one manipulates symbols, as in algebra. Instead of writing "All men are mortal," one puts down ab[1] = 0, and works through the problem as one involving technical relations be-

[1] William Tell's note: The "b" is supposed to have a bar above it.

tween classes. Symbolic logic has been intensively developed in recent years, to become "a wonderful streamlined mathematical machine."[2]

Meanwhile, two Polish mathematicians, Tarski and Lukasiewics, perfected about 1930 a consistent "multi-valued" logic, which turned out to be much more flexible than some of the older two-valued varieties.

THINKING IN TERMS OF PROCESS

The old logic, because it tends to proceed from a single cause to a given effect, is sometimes called linear thinking. Today scientists find such thinking too limited. A given effect -- whether a stomach-ache or a revolution -- may be the result of many causes, and in turn produces still further effects. A kind of spiraling process appears, with one cause reinforcing another.[3] Or a series of effects may occur, and one tend to block another. In medicine, for instance, a new drug may perform a miracle in clearing up an infection, but break down the body's resistance to other disorders. Similarly, in the field of social science, one should not look for a single cause for juvenile delinquency; various processes are at work, and remedies must be sought accordingly.

THINKING IN RELATIONSHIPS

Einstein in his demonstration of relativity showed that time changes with velocity; the faster you go, the longer the time interval. If you could travel at the speed of light, 186,000 miles per second, you could theoretically live forever. This conclusion takes us into high-speed physics, but the relativity idea applies all down the line.

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[2] Hugh and Lillian Lieber, *Mits, Wits and Logic*.

[3] "Rope reasoning" is a graphic nickname applied to some of these new types of thinking.

A simple illustration to show the relativity of "hot" and "cold" is that of the three pails. Put very cold water in one pail, very hot in another, and tepid water in the third. Dip your right hand for a moment in the hot water, then in tepid. How does it feel? *Cold!* Now hold your left hand first in the cold water and then in the tepid. How does it feel? *Hot!* The same pail of water can produce sensations either "hot" or "cold," depending on where your hand has last been. It is the relation which counts, rather than any absolute property of "coldness" or "hotness."

OPERATIONAL DEFINITIONS

Those of us who are not mathematicians and experts in symbolic and multi-valued logic find the scientists' "operational definition" especially useful. As described by Bridgman in *The Logic of Modern Physics,* it is a method for defining the terms we use in science, or indeed in any serious discussion. A term which is not susceptible to an operational definition usually remains fuzzy, if not completely meaningless. This distinction saves endless hours of debating about things which, while they may sound meaningful enough, can never really be pinned down.

When a scientist, says Bridgman, is asked to define such a term as "length" he does not go to the dictionary; he does not even open his mouth. He performs certain operations with his hands, using clocks or meter sticks or whatever instruments are necessary. The definition grows out of what he *does*: "Look, here is what I mean by length." "Length" turns out to have several meanings, one for stable things like a house, another for moving things like a Greyhound bus, another for stellar distances.

This approach is full of lessons for straight thinkers. *If no operation can be performed, it is highly improbable that two* *human minds can get close enough to the subject to discuss it intelligently.* A bull session may be amusing, but on such a subject it cannot get much of anywhere. Some scholars do not agree with this assertion; but Bridgman insists it is the only way that physicists can use their reason profitably on many problems. He gives us samples of questions which were meaningless in physics, and are likely to remain so for some time:

> What is the ultimate nature of matter?
> Was there ever a time when matter did not exist?
> Why does time flow?
> May space or time be discontinuous?
> Are there parts of nature forever beyond our detection?
> Is a universe possible in which laws are different?

You can take a carload of meter sticks, stop watches, and Geiger counters, but you will not be able to perform operations to give such questions meaning. So they can be skipped -- except in the aforesaid bull sessions.

We can skip many in the field of social sciences, too, using Bridgman's touchstone:

> Is thought possible without language?
> Is environment more important than heredity?
> What is economic value?
> Is his difficulty physical or mental?

We can make guesses about these questions, and perhaps enjoy an interesting give-and-take, but no operation can be performed to give them exact meaning. At least none has yet been found.

THE TOOL OF SEMANTICS

The last technique we shall touch on in this brief review is semantics, defined as "the systematic study of meaning." It is concerned with what a speaker *means* as well as what he says — a point overlooked by many of the classicists. Semantics is only one of a group of disciplines concerned with communication, others being linguistics, cybernetics, perception theory, and so on.[4]

The student of semantics analyzes some of the roadblocks which held up the old logicians. If the giants of the Hellenic world had been more aware of the relativity of language, we might all be further along. Semantics is deeply concerned with the use and abuse of abstract terms. It has invented so-called "abstraction ladders," to indicate how far one's words may be from the concrete event under discussion. Semantics also charts various dangers in two-valued thinking, and in false identification. It can be applied in sifting charges of guilt by association, and guilt by kinship. It is useful too in the analysis of "gobbledygook," the clouding of meaning by fancy language. It is invaluable in analyzing campaign oratory, double-talk, high-speed propaganda, and the arts of demagogues. It is very helpful in spotting logical fallacies.

Caught in the toils of language, without adequate mathematics, laboratories, instruments, without the concept of probability, process, and relativity, it is remarkable that scientists before Galileo discovered as much as they did, and not at all surprising that philosophers ran off the track from time to time.

Some of us today seem to be content to go along with the Sophists and the Schoolmen, but others are using the logic of modern science to gain a better understanding of our world.

[4] My book, *Power of Words*, 1954, describes a dozen disciplines in the field of communication.