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KNOWLEDGE

GAINING NEW KNOWLEDGE

Knowledge can be acquired by humans in many ways. Surely, there are also many ways to classify the means to acquire knowledge. Here are just a few ways.

One's brain can acquire knowledge during the evolutionary process by successive modifications to the genes. That finally results in fertilization of egg by sperm and the gestation process in the mother. Certainly, all this depends on the sensory–motor "operating system" software that makes the sense organs and muscles work together. But evolution also plays at the level of higher cognitive function. As Noam Chomsky has shown us (Chomsky, 1957), much of the syntactic structure of grammar is evidently built in at birth. What knowledge we acquire after birth is a function of what we attend to, and what we attend to is a function of our motivation for allocating our attention, which ultimately is a function of what we know, so knowledge acquisition after birth is a causal circle.

Learning has to do with how we respond to the stimuli we observe. Perhaps, the oldest theory of learning is the process of Pavlovian (classical) conditioning, where a stimulus, originally neutral in its effect, becomes a

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signal that an inherently significant (reward or punishment) unconditioned stimulus is about to occur. This results only after multiple pairings, and the brain somehow remembers the association. The originally neutral stimulus becomes conditioned, meaning that the person (or animal) responds reflexively to the conditioned stimulus the same as the person would respond to the unconditioned stimulus (e.g., the dog salivates with the light or bell).

A different kind of learning is Skinnerian or *operant* conditioning (Skinner, 1938). This is where a voluntary random action (called a free operant) is rewarded (reinforced), that association is remembered, and after sufficient repetitions, the voluntary actions occur more often (if previously rewarded). Operant learning can be maintained even when rewards are infrequently paired with the conditioned action.

There are many classifications of learning (http://www.washington.edu/doit/types-learning). Bloom et al. (1956) developed a classification scheme for types of learning which includes three overlapping domains: cognitive, psychomotor, and affective. Skills in the cognitive domain include *knowledge* (remembering information), *comprehension* (explaining the meaning of information), *application* (using abstractions in concrete situations), *analysis* (breaking down a whole into component parts), and *synthesis* (putting parts together to form a new and integrated whole).

Gardner (2011) developed a theory of multiple intelligences based upon research in the biological sciences, logistical analysis, and psychology. He breaks down knowledge into seven types: *logical–mathematical intelligence* (the ability to detect patterns, think logically, reason and analyze, and compute mathematical equations), *linguistic intelligence* (the mastery of oral and written language in self-expression and memory), s*patial intelligence* (the ability to recognize and manipulate patterns in spatial relationships), *musical intelligence* (the ability to recognize and compose music), *kinesthetic intelligence* (the ability to use the body or parts of the body to create products or solve problems), *interpersonal intelligence* (the ability to recognize another's intentions and feelings), and *intrapersonal intelligence* (the ability to understand oneself and use the information to self-manage).

Knowledge can be public, where two or more people agree on some perception or interpretation and others can access the same information. Or it can be private, where it has not or cannot be shared. The issue is tricky, and that is why modelability is proposed as a criterion for what can be called public knowledge. Two people can look at what we call a red rose, and agree that it is red, because they have learned to respond with the word *red* upon observing that stimulus. But ultimately exactly what they experienced cannot be shared, hence is not public.

We can posit that some learning is simply accepting, unquestioningly, information from some source because that source is trusted or because the learner is compelled in some way to learn. We finally contrast the aforementioned models to learning by means of the scientific method, which is detailed in the following text. Critical observation and hypothesizing are followed by collection of evidence, analysis, logical conclusions, and modeling to serve one's own use or to communicate to others.

SCIENTIFIC METHOD: WHAT IS IT?

How to determine the truth? Science has its own formal model for this. The scientific method is usually stated as consisting of nine steps as follows:

1. Gather information and resources (informal observation).
2. Question the relationships between aspects of some objects or events, based on observation and contemplation. An incipient mental model may already form in the observer's head.
3. Hypothesize a conjecture resulting from the act of questioning. This can be either a predictive or an explanatory hypothesis. In either case, it should be stated explicitly in terms of independent and dependent variables (causes and effects).
4. Predict the logical consequences of the hypothesis. (A model will begin to take shape.)
5. Test the hypothesis by doing formal data collection and experiments to determine whether the world behaves according to the prediction. This includes taking pains to design the data-taking and the experiment to minimize risks of experimental error. It is critical that the tests be recorded in enough detail so as to be observable and repeatable by others. The experimental design will have a large effect on what model might emerge.
6. Analyze the results of the experiment and draw tentative conclusions. This often involves a secondary hypothesis step, namely exercising the statistical *null hypothesis*. The null hypothesis is that some conjecture about a population of related objects or events is false, namely that observed differences have occurred by chance, for example, that some disease is not affected by some drug. Normally, the effort is to show a degree of statistical confidence in the failure and thus rejection of the null hypothesis. In other words, if there is enough confidence that the differences did not occur by chance, then the conjectured relationship exists.

7. Draw formal conclusions and model as appropriate.
8. Communicate the results, conclusions, and model to colleagues in publication or verbal presentation, rendering the model in a form that best summarizes and communicates the determined relationships.
9. Retest and refine the model (frequently done based on review and critique by other scientists).

FURTHER OBSERVATIONS ON THE SCIENTIFIC METHOD

The scientific method described earlier is also called the *hypothetico-deductive* method. As stated, it is an idealization of the way science really works, as the given scientific steps are seldom cleanly separated and the process is typically messy. Often experimentation is done in order to make observations that provoke additional observations, questions, hypotheses, predictions, and rejections or refinements of the starting hypothesis. Especially at the early observation stage, the process can be very informal. One of the writer's students used to say that what we did in the lab was "piddling with a purpose." Einstein is said to have remarked that the most important tool of the scientist is the wastebasket.

Philosopher statesman Francis Bacon (1620) asserted that observations must be collected "without prejudice." But as scientists are real people, there is no way they can operate free of some prejudice. They start with some bias as to their initial knowledge and interests, their social status and physical location, and their available tools of observation. They are initially prejudiced as to what is of interest, what observations are made, and what questions are asked.

Philosopher Karl Popper (1997) believed that all science begins with a prejudiced hypothesis. He further asserted that actually a theory can never be proven correct by observation, but it can only be proven incorrect by disagreement with observation. Scientific method is about falsifiability. That is the basis of the null hypothesis test in statistics. (But, of course, the falsifiability is itself subject to statistical error; one can only reject the null hypothesis with some small chance of being wrong.) The American Association for the Advancement of Science asserted in a legal brief to the U.S. Supreme Court (1993) that "Science is not an encyclopedic body of knowledge about the universe. Instead, it represents a process for proposing and refining theoretical explanations about the world that are subject to further testing and refinement."

Historian Thomas Kuhn (1962) offered a different perspective on how science works, namely, in terms of *paradigm shifts*. Whether in psychology or cosmology, researchers seem to make small and gradual refinements of accepted models, until new evidence and an accompanying model provokes a radical shift in paradigm, to which scientists then adhere for a time. When a new paradigm is in process of emerging the competition between models and their proponents can be fierce, even personal (who discovered X first, who published first, whose model offers the best explanation). We also must admit that search for truth is not the only thing that motivates us as scientists and modelers. We are driven by ambition for recognition from our peers as well as by money.

The idea of *reproducible observability* deserves emphasis. Having to deal with observables is the most critical factor in an epistemological sense (what we know). This is because it distinguishes what may be called truth based on scientific evidence that is openly observable from experiences that are not observable by others (e.g., personal testimony and anecdotal evidence). Observability also comes into play for what are called mental models.

Mental models can be called models of a sort, but being private they are not subject to direct observation by other people. Experiments in psychophysics, where subjects make verbal category judgments or button-push responses to physical stimuli of sound, light, and so on, are regarded as conforming to scientific method. This is because the human is making a direct mechanical response to a given stimulus, such as pushing a button, not having to articulate in arbitrary words what the human is thinking. However, when subjects are asked to explicate in their own words their mental models of how they believe something works, or what are cognitive steps of a particular task as might be asked of subject matter experts, there is no external physical reference; scientific method here is more challenging. Of course, there must be repeatability or aggregation of the results from many subjects. Observability clearly is a challenge for modeling.

While social scientists often point out that humans have a predilection for reaffirming the *status quo*, science nevertheless is a truth system committed to change, as warranted, rather than preservation. But while science actively pursues possibilities of change, the null hypothesis testing by its very nature demands a significant level of statistical confidence in order to reject the null hypothesis that there is no real change (that there is only random difference between the hypothesized variant and the control).

The scientific method is a method wherein inquiry regards itself as fallible and purposely probes, criticizes, corrects, and improves itself. This universally accepted attribute stands in sharp contrast to religious and political traditions around the world. Science is the one human endeavor that has proven relatively immune to the passions that otherwise divide us.

REASONING LOGICALLY

One can derive a model by logical reasoning or it may be stated out of ignorance or for purposes of deception. It may also be a metaphorical model, where, because of ambiguity in the words or drawings, it is not possible to conclude that it is logical. If it is based on logic and assuming no ambiguity in the words, pictures, or symbols, it is relevant to mention three different types of logical reasoning: deduction, induction, and abduction.

Deduction allows deriving b from a only where b is a formal logical consequence of a. In other words, deduction is the process of deriving the consequences of what is assumed. Given the truth of the assumptions, a valid deduction guarantees the truth of the conclusion. For example, given that all bachelors are unmarried males, and given that some person is a bachelor, it can be deduced that that person is an unmarried male.

Induction allows inferring b from a, where b does not follow necessarily from a. The existence of a might give us very good reason to accept b, but it does not ensure that b is true. For example, if all of the swans that we have observed so far are white, we may induce that all swans are white. We have good reason to believe the conclusion from the premise, but the truth of the conclusion is not guaranteed. (Indeed, it turns out that some swans are black.)

Abduction allows inferring a as an explanation of b. Put another way, abduction allows the precondition a to be abduced from the consequence b. Deduction and abduction thus differ in the direction in which a rule like "a entails b" is used for inference. As such, abduction is formally equivalent to a logical fallacy that a unique a occurs where actually there are multiple possible explanations for b. For example, after glancing up and seeing the eight ball moving in some direction we may abduce that it was struck by the cue ball. The cue ball's strike would account for the eight ball's movement. It serves as a hypothesis that explains our observation. There are in fact many possible explanations for the eight ball's movement, and so our abduction does not leave us certain that the cue ball did in fact strike the eight ball, but our abduction is still useful and can serve to orient us in our surroundings. This process of abduction is an instance of the scientific method. Logically, there are infinite possible explanations for any of the physical processes we observe, but from our experience we are inclined to abduce a single explanation (or a few explanations) for them in the hopes that we can better orient ourselves in our surroundings and then eliminate some of the possibilities by further observation or experiment.

PUBLIC (OBJECTIVE) AND PRIVATE (SUBJECTIVE) KNOWLEDGE

Model development necessarily begins in the head of some person, and only later is the model rendered in words, graphics, or mathematical language so that it can be communicated to others. The term *mental model* refers broadly to a person's private thoughts, though some psychologists would confine its use to well-formed ideas about the structure or function of some objects or events, such that it is potentially communicable in understandable format to another person.

Psychologists have struggled for many years with how to extract a person's mental model. Psychophysical methods of having experimental subjects' rank-order stimuli or assign preferential numbers or descriptive categories (as done by political pollsters) are a common approach. With more complex situations, and particularly those that have social implications, a problem is that what people say they believe and what they actually believe may be quite different. People are inclined to say what they think some other person wants to hear; social etiquette reinforces this behavior. Later in the book, Chapter 10 deals with mental models in more detail.

THE ROLE OF DOUBT IN DOING SCIENCE

For many years, philosophers, from Rene Descartes to Charles Sanders Peirce (2001), have proposed *methodological doubting* (also called *Cartesian skepticism*, *methodological skepticism*, or *hyperbolic doubt*) as a means to test the truth of one's beliefs. I recall attending a "Skeptics Seminar" at MIT at which the famous mathematician and founder of cybernetics Norbert Wiener emphasized the importance of doubting in order to refine one's beliefs.

Doubt is deliberation on error and failure. Together with a graduate student, I once offered an experimental graduate course called "Seminar on Failure" in which historians, psychiatrists, scientists, and engineers were invited to reminisce on failures in their own professional experiences. We learned that failure often led to discovery and learning, and that success often led to overconfidence and carelessness and eventually to failure. Failure and success are the Taoist yin and yang of our experience; they are mutually complementary; one could not exist without the other.

Doubt and questioning motivate scientists to think of different hypotheses and try different experiments. Pioneer in cybernetics Ross Ashby (1956) is known for his "law of requisite variety," which asserts that in order for one system to control another it must possess a greater variety of states. This law has been applied to genetic mutations believed to be essential to the evolution of species as per Darwin's theory. There is requisite variety in our own social and environmental encounters in life, from which we can refine our beliefs and models of what works and what does not work. Edwin Hubble's doubt led to the discovery that the brightness of a spot in the Andromeda cluster could not be from our own galaxy, the first proof that there were other galaxies in the universe. Sometimes, it is not simply doubt but absolute failure that provokes a wider search for solution and improvement, whether in a computer or a person.

EVIDENCE: ITS USE AND AVOIDANCE

It might be assumed that rational people accept a model or a belief because the preponderance of evidence supports that model or belief. But people are always free to "choose" a belief because it is what parents or peers say they believe, or what individuals believe they should believe, for whatever reason. Perhaps, it is because they think believing will make them feel better, or there will be punishment for professing disbelief. But these are not acts of seeking truth. No one says that truth-seeking is easy, particularly when what appears to be the rational truth is in conflict with claims by authority figures or other trusted sources.

Surely, truth-seeking has its costs. In many ways, evolution has designed us not to be rational in every act. Hyper-rational insistence on bare-faced truth clearly gets us into trouble—in interpersonal relations where etiquette is required, in supporting and defending a child from destructive criticism, in winning an argument, and so on. The truth may be messy and ugly. Some will surely feel that absolute truth is second to happiness, and who will ever know the ultimate truth anyway? Isn't happiness the real goal? In any case, we may want to be careful about flaunting what we believe to be the truth.

METAPHYSICS AND ITS RELATION TO SCIENCE

Metaphysics is a traditional branch of philosophy concerned with being—what things exist and what are their properties. Prior to the eighteenth century, all questions of ultimate reality were addressed by philosophers. Aristotle believed that things have within them their own purpose (a teleology). He is well known for distinguishing between two essential properties of things: potentiality (the possibility of any property a thing can have) and actuality (what is actually in evidence). There are modern manifestations of Aristotle's dichotomy, such as the distinction between potential and kinetic energy in physics. Thomas Aquinas called metaphysics the "queen of sciences" and wrote extensively on the subject.

Ever since the Enlightenment, the field of metaphysics has evolved into a philosophical pursuit of topics that have not been easy for science to handle, such as being (existence), mind, perception, free will, consciousness, and meaning. Science has begun to confront some of these issues. Whether over time they will be clarified remains as a conundrum, or whether the verbal constructs will just fade away remains to be determined. I would guess some of each.

Descartes' famous conclusion that "I think, therefore I am" was proffered as a metaphysical basis for his own existence. He asserted that while all else could be doubted, the fact that he could do the doubting meant that he must exist in order to doubt. Such thought experiments are common in philosophy. One famous thought experiment allowed that to imagine a thing or event is to make it exist, namely the famous "proof of God" offered by Anselm of Canterbury. Surely, thoughts do exist as neural activity in the brains of people who have the thoughts; they constitute what we have called mental models. But our concern here is mostly for deducing the existence of things perceived from observables, with the exception of "mental models," which are dealt with separately in Chapter 10.

OBJECTIVITY, ADVOCACY, AND BIAS

Ideally, the scientist is supposed to be disinterested, completely impartial to how any test of a hypothesis turns out, and what the implications of the results are for the world. But scientists are people, and people do things because they are interested in achieving some objectives. The very act of formulating a hypothesis is a creative act, motivated by the interests of the scientist. But given this unavoidable level of interest, the scientist has an obligation to be as objective as possible, and not favor one aspect of the results while hiding some other aspect.

In truth, everyone is subject to bias, including this author. Psychologists have studied human biases extensively. In dealing with value-laden topics, biases are especially salient. One most pertinent category of bias is what is called the *confirmation bias*. Nickerson (1998) defines the confirmation bias as "the seeking or interpreting of evidence in ways that are partial to existing beliefs, expectations, or a hypothesis in hand." He reviews evidence of such a bias in a variety of guises and gives examples of its operation in several practical contexts. Other biases include overconfidence in one's own predictions, giving more weight to recent events as compared to earlier events in judging probabilities, ascribing greater risk to situations one is forced into as compared to those voluntarily selected, and inferring illusory causal relations.

Many democratic societies have judicial systems based on advocacy, where the advocates of the two or more sides of any argument confront one another in a highly procedural venue in front of a jury of peers. The assumption is that the jury can judge the arguments, weigh the evidence presented, and detect efforts to hide something. Because conventional jury selection is not set up to include experts on particular fields of science or technology, there have been various proposals to develop "science courts" that would somehow demand more rigorous objectivity in presenting and judging arguments and evidence.

ANALOGY AND METAPHOR

Analogy is a broad class of cognitive process or linguistic expression involving transfer of meaning from one object or event to another because of some similarity. Analogy plays a critical role in creativity, problem solving, memory, perception, explanation, and communication.

Science depends on metaphor (and simile) in the sense that an active and curious observer is constantly seeing analogies, likenesses between elements of nature. The observed likenesses lead to hypotheses that permit generalization.

For example, in the field of physics, mechanical force, pressure, electrical voltage, and temperature are all seen as having the property of effort. Mechanical velocity, fluid flow, electrical current, and heat flow are all seen as having the property of flow. Mechanical friction, fluid viscosity, electrical resistance, and thermal insulation all have the property of resistance to flow. Depending on the spatial configuration, the equations relating the forces, flows, and resistance to flow are the same (to a first approximation), namely

$$\text{Effort} = \text{flow} \times \text{resistance}$$

Such analogies are powerful concepts in physical science that also have counterparts in traffic analysis, economics, and other fields. Much academic teaching in the physical sciences and engineering employs analogy.

Metaphor is a figure of speech that makes use of analogy. It is a word or phrase describing a thing or an action that is regarded as representative or symbolic of something else, especially something abstract—even though it is not literally applicable. This is in contrast to a simile, in which something is said to be like something else, and the attribute of likeness is spelled out or implied. Joseph Campbell (1949) uses the following examples: The boy runs like a deer (simile). The boy is a deer (metaphor).

Metaphor finds its place in literature, poetry, music, and the arts; they depend on metaphor. Metaphor can say things more emotionally powerful than simple rational statements. Metaphor provokes the human imagination, as in myths, allegories, and parables. It has been said that literature and the arts often realize human truths well before other branches of human endeavor do. Since it is a figure of speech, a metaphor is not a belief (a mental event); rather it is a way to describe a belief. Things are not metaphors but can be expressed through metaphors. Every metaphor is both metaphorically true (if it is an apt description) and literally false.

An analog representation, whether in words or any other medium, can be a model. This author cut his academic teeth using analog computer operations as models of human behavior. The point is that certain relationships (e.g., in magnitude and time of the graphical traces generated by the analog computer) denote magnitude and time relationships of the target thing or events being modeled. It is understood by the user of the analog computer that other properties of the analog computer (physical hardware, electron flow) are irrelevant.

Metaphorical description can be a kind of model, though not a scientific model, as previously noted. This is because the interpretation of the metaphor as a representation of the target object or event is a creative act by the reader or listener, since the connection between the metaphor and the target is not explicit (it is connotative). For example, religious myth fits this category.