The Origins of the Scientific Method

Scientific knowledge is defined by a methodology, and to understand this methodology, we must examine its roots and development. Francis Bacon's text *Novum Organum*, written almost four hundred years ago, prophesied the modern scientific method, but it can be understood only in relation to the tradition of Scholastic natural philosophy against which Bacon was reacting.

The Scholastics deployed a combination of Christian theology and classical works—viewing Aristotle as a secular intellectual giant without equal—to try to explain the physical world around them. They viewed any material body as comprising both an inert substratum of primary matter and a quality-bearing essence—its substantial form. The substantial form is what enables the body to interact causally with other bodies. Any material object, for example, possesses weight, color, texture, and all of the other bodily properties, only in virtue of being conjoined with a substantial form of a loaf of bread, bowling ball, chair, or whatever. There is some “essence” of the bowling ball that makes it different from the loaf of bread.

To a modern reader, this sounds like a bunch of gobbledygook, but it resulted from Aristotle’s confrontation with a profound mystery. In *Physics*, he asked by way of example why front teeth regularly grow sharp, and back teeth broad, in a fashion that is good for an animal. He claimed that we must go beyond just the interaction of particles, because it cannot simply be coincidence that this arrangement would arise so regularly. Aristotle argued that the formation of the parts of the animal in a manner that is good for the animal requires the existence of what he called a final cause that is “the end, that for the sake of which a thing is done.” Some essence of the animal causes interacting particles to organize themselves differently for this animal than for the rock next to it that is also composed of interacting particles. Hence the need for a substantial form that distinguishes the animal from the nearby rock. This was the dominant intellectual method for understanding natural phenomena from the ancient Greeks to Bacon.

Bacon’s central argument was not exactly that this was wrong, but rather that it was impractical. He argued that scientists would be more productive if they ruled questions about things like final causes to be out of bounds; if they narrowed the scope of natural philosophy by considering such questions to be metaphysics rather than physics. He was correct. And this turns out to have been one of the most consequential insights in human history.

Bacon was not an ivory-tower philosopher. In addition to his work as a thinker, he was a politician, serving as attorney general and lord chancellor under King James I. It is therefore not surprising that he believed that “the true and lawful goal of the sciences is none other than this: that human life be endowed with new discoveries and powers.” Although he did not deny the aesthetic pleasures of scientific discovery and understanding, he viewed science primarily as a tool to “extend more widely the limits of the power and greatness of man.”

When Bacon produced *Novum Organum* in 1620, his take on the utility of Scholastic natural philosophy in achieving practical progress was withering:

The sciences which we possess come for the most part from the Greeks . . .

Now, from all these systems of the Greeks, and their ramifications through particular sciences, there can hardly after the lapse of so many years be adduced a single experiment which tends to relieve and benefit the condition of man, and which can with truth be referred to the speculations and theories of philosophy. And Celsus ingenuously and wisely owns as much when he tells us that the experimental part of medicine was first discovered, and that afterwards men philosophized about it, and hunted for and assigned causes; and not by an inverse process that philosophy and the knowledge of causes led to the discovery and development of the experimental part . . .

Some little has indeed been produced by the industry of chemists; but it has been produced accidentally and in passing, or else by a kind of variation of experiments, such as mechanics use, and not by any art
or theory. For the theory which they have devised rather confuses the experiments than aids them.

He was trying to contrast lack of progress with something we now take for granted but at the time was entirely theoretical: rapidly advancing scientific knowledge. Simply seeing this possibility was a triumph of the imagination, but his greatest intellectual achievement was to lay out a program to achieve it.

To help explain why progress had thus far been limited, Bacon began with a theory that combined two key elements. The first was the observation that nature is extraordinarily complicated as compared to human mental capacities, whether those of individuals (“the subtlety of nature is greater many times over than the subtlety of the senses and understanding”) or those of groups (“the subtlety of nature is greater many times over than the subtlety of argument”). The second element of his theory was his belief that humans tend to overinterpret data into unreliable patterns and therefore leap to faulty conclusions, saying that “the human understanding is of its own nature prone to suppose the existence of more order and regularity in the world than it finds.” He argued that science should therefore proceed from twin premises of a deep epistemic humility and a concomitant distrust of the human tendency to leap to conclusions.

Bacon believed that this combination of errors had consistently led natural philosophers to enshrine premature theories as comprehensive certainties that discouraged further discovery. Proponents of alternative theories, all of whom had also made faulty extrapolations from limited data to create their theories, would then attempt to apply logic to decide between them through competitive debate. The result was a closed intellectual system whose adherents spent their energies in ceaseless argumentation based on false premises, rather than seeking new information. He describes the method of natural philosophy from the Greeks to his day as follows:

From a few examples and particulars (with the addition of common notions and perhaps of some portion of the received opinions which have been most popular) they flew at once to the most general conclusions, or first principles of science. Taking the truth of these as fixed and immovable, they proceeded by means of intermediate propositions to educe and prove from them the inferior conclusions; and out of these they framed the art. After that, if any new particulars and examples repugnant to their dogmas were mooted and adduced, either they subtly molded them into their system by distinctions or explanations of their rules, or else coarsely got rid of them by exceptions; while to such particulars as were not repugnant they labored to assign causes in conformity with those of their principles.

Bacon hammered at this point to a degree that can seem repetitive to a modern reader, but that’s because we live within the scientific framework that he envisioned. He was arguing against a 2,000-year tradition of what formal knowledge of the physical world was—not in the sense of a list of facts, but more profoundly, in the way of knowing it.

Building upon the first glimmerings of the scientific revolution in Europe, Bacon proposed a new method (novum organum) that would start with the meticulous construction of factual knowledge as a foundation for belief and would then rise “by a gradual and unbroken ascent, so that it arrives at the most general axioms last of all.” He called this method induction. The practical manifestation of his proposed approach came to be called the scientific method.

He was clear that implementing this approach would not be easy, and his attempts to foresee what would be required were astoundingly insightful.

First, and most philosophically momentous, was the shift from the Scholastic emphasis on inherently different natures of different classes of objects to an emphasis on how material objects can be observed to interact. In a criticism of the Scholastics, Bacon put this as: “But it is a far greater evil that they make the quiescent principles, wherefrom, and not the moving principles, whereby, things are produced, the object of their contemplation and inquiry. For the former tend to discourse, the latter to works.” In modern language, he was expressing the viewpoint
that scientists should proceed *as if* they are pure materialist reductionists, *as if* all observable reality can be reduced to particles plus rules for their interaction. Note that he argued that they should do this not because it is more accurate in some philosophical sense, but because it "tends to works." The ultimate goal of Baconian science is not philosophical truth; it is improved engineering.

Second, Bacon understood that science is a human activity that would require a certain mind-set on the part of scientists. Scientists would have to believe that deep knowledge of the physical world was accessible to them through these methods, since "by far the greatest obstacle to the progress of science . . . is found in this—that men despair and think things impossible." Further, he argued that they should not be limited in their subjects of inquiry into the material world, since "whatever deserves to exist deserves also to be known." He described in these passages the person of boundless curiosity who has confidence that he can and should discover the mysteries of the natural world through the scientific method—that is, the modern scientist. He called such people the "true sons of knowledge."

Third, Bacon saw science not only as a human enterprise, but more specifically as a social enterprise, since this endeavor was "one in which the labors and industries of men (especially as regards the collecting of experience) may with the best effect be first distributed and then combined. For then only will men begin to know their strength when instead of great numbers doing all the same things, one shall take charge of one thing and another of another." In a later book, *New Atlantis*, he even described a model for the modern state-supported research university with specialized departments and laboratories, which he called Salomon's House.

Fourth, Bacon had a clear understanding of the roles of what today we call basic and applied research. Although he saw the ultimate goal of science as material benefit, he believed that, paradoxically, focusing on slowly building sufficient experimental knowledge to develop general physical laws ("experiments of Light"), rather than trying to immediately solve specific practical problems ("experiments of Fruit"), would lead to the greatest progress over time. Further, he had the supple un-

derstanding that the relationship between basic and applied research would not be one of linear progress from basic research to applied research, but that these would interact and feed off each other in complex and unpredictable ways, saying, "Let no man look for much progress in the sciences—especially in the practical part of them—unless natural philosophy be carried on and applied to particular sciences, and particular sciences be carried back again to natural philosophy."

Fifth, and of the most practical methodological importance, he asserted the primacy of careful experiments as the initial building blocks of scientific knowledge. He contrasted his proposed approach with prior natural philosophy: "Both ways set out from the senses and particulars, and rest in the highest generalities; but the difference between them is infinite. For the one just glances at experiment and particulars in passing, the other dwells duly and orderly among them." He described experimental rigor in the negative, by highlighting those elements of observation in prior natural philosophy that he considered deficient, saying that "nothing duly investigated, nothing verified, nothing counted, weighed, or measured, is to be found in natural history; and what in observation is loose and vague, is in information deceptive and treacherous." He proposed, instead, that experimentation "shall proceed in accordance with a fixed law, in regular order, and without interruption."

Bacon's degree of focus on experimentation at the expense of theorizing can be caricatured. Although he was trying to advance the prominence of careful experiments in creating knowledge, he clearly saw that scientific progress would rely upon an intimate combination of theory and experiment, arguing that "from a closer and purer league between these two faculties, the experimental and the rational (such as has never yet been made), much may be hoped."

But how exactly should experiments be conducted and then combined to create reliable physical laws? It was not until many years later that the concept of the controlled experiment (carefully changing only one potential causal factor and observing the result) was more rigorously distinguished from nonexperimental observation than in Bacon's somewhat impressionistic "verified, weighed, and counted" description.
But the core problem is always how we can generalize reliably from a series of observations, experimental or otherwise, to general principles.

Bacon was, of course, keenly attuned to the centrality of this issue; remember that his fundamental critique of the Scholastics was inappropriate generalization from “a few examples and particulars” to “general conclusions.” He recognized that generalization must be done to construct the predictive rules that enable science to create practical benefits, saying that “the induction is amiss which infers the principles of sciences by simple enumeration.” But Bacon warned scientists that if his program was implemented, the danger of inappropriate generalization would dog them.

Bacon attempted to define a process of scientific experimentation and inference, but in this he failed; the detailed method he proposed has not been used by scientists in practice. He was never able to explain exactly how the induction of general physical laws from individual observations should work at an algorithmic or logical level. As we’ll see, however, the process of scientific discovery turns out to be quite tricky to describe, and resists such algorithmic description. It was only hundreds of years later that philosophers, armed with the enormous advantage of observing science as it was actually conducted, were able to address somewhat more satisfactorily the problem of what Sir Karl Popper would come to call “the logic of scientific discovery.”

The Problem of Induction

Writing a little more than a century after Bacon, skeptical British philosopher David Hume focused on the problem of how we can generalize from a finite list of instances to a general rule in *An Enquiry Concerning Human Understanding*. He first established, consistent with Bacon’s point that “simple enumeration” is not what we’re after, that the development of cause-and-effect rules is central to practical knowledge:

> All reasonings concerning matter of fact seem to be founded on the relation of Cause and Effect. By means of that relation alone we can go beyond the evidence of our memory and senses... This relation is either near or remote, direct or collateral. Heat and light are collateral effects of fire, and the one effect may justly be inferred from the other.

Hume then proceeded to make a second point: we can never be sure of a cause-and-effect rule developed through induction. In one of the most famous paragraphs in modern philosophy, he provided a non-abstract illustration of why:

> Our senses inform us of the colour, weight, and consistence of bread; but neither sense nor reason can ever inform us of those qualities which fit it for the nourishment and support of a human body... If a body of like colour and consistence with that bread, which we have formerly eat, be presented to us, we make no scruple of repeating the experiment, and foresee, with certainty, like nourishment and support. Now this is a process of the mind or thought, of which I would willingly know the foundation. It is allowed on all hands that there is no known connexion between the sensible qualities and the secret powers; and consequently, that the mind is not led to form such a conclusion concerning their constant and regular conjunction, by anything which it knows of their nature. As to past Experience, it can be allowed to give direct and certain information of those precise objects only, and that precise period of time, which fell under its cognizance: but why this experience should be extended to future times, and to other objects, which for aught we know, may be only in appearance similar; this is the main question on which I would insist.

In modern language, we might say that just because I’ve been nourished every time I’ve eaten a thing that is brown, tastes bready, and is shaped like a loaf, how do I know that the next time I eat something of this description it will nourish me?

One could argue that this is outdated because modern biology and chemistry have in fact identified the specific chemical components of the bread that make it nutritious. But how do we know that these chemicals, when supplied in normal quantities and manner, will be nutritious? Well,