The Scientific Enterprise

9. The Role of Instruments in Science

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Introduction

A major strategy of science in its efforts to know and unravel the secrets of the phenomenal world is in the devising and utilization of a whole array of gadgets and instruments. It must be emphasized that other modes of knowing the world, however profound, insightful, and interesting they may be, do not use instruments specially constructed for a purpose such as the world of science uses. In this respect again scientifically acquired knowledge and worldviews are categorically different from what is obtained from other means.

The Goals of Scientific Instruments

A scientific instrument is an ingeniously contrived device, using material things and their properties, for specific purposes. In general, the goal of a scientific instrument could be one or more of the following:

(a) ***Uncovering type*****:** Survey your surroundings and list whatever you see and hear and taste, and all that you can smell and touch. The list will never include everything there is around you because there are entities of whose existence we can't become aware through the normal modes of perception. Thus, for example, your environment might include some helium and argon, some ultraviolet radiation and certainly lots of microwaves. The clear sky above on a bright sunny day has lots of stars high above which we can't see even in the pitch-darkness of night. However, with appropriate instruments, all these and much more can be unraveled. Human knowledge about the existence and properties of many features of the world has expanded enormously through the use of scientific instruments. It is thanks to instruments that we know of Jupiter's moons, of Uranus, Neptune and Pluto, of the Earth's magnetic field, of cosmic rays, of microbes and viruses, and other such entities of which pre-instrument humanity did not even dream. (Ivan Amato, *Super Vision: A New View of Nature*, Harry N Abrams, Inc., New York, 2003.)

(b) ***Metrical type*****:** Measurement is the lifeblood of science. When philosophers and critics of scientific knowledge talk about the limits of science, they generally have very little idea of the precision and measurements involved in scientific observations. Instruments are essential for making precise and quantitative observations of phenomena. A significantly deeper understanding of the nature of phenomena is obtained by taking into account their quantitative features whenever and wherever possible.

Length, mass, and time are the most basic measurable quantities in the physical world. They have been measured since ancient times, for they are also useful in trade and in the fixing of auspicious days and hours. Land areas for reckoning how much grain is to be cultivated, the time it takes for the grains to sprout, and the amount (mass) of grains harvested: all these have been measured since the remote past. Add to these the electric charge, and we have what are called the fundamental dimensions of the physical world. Physics has added one more dimension to these natural dimensions: *temperature*. Using these as the foundational bricks, physicists have defined countless other physical (measurable) quantities, such as volume and speed, force, momentum and specific heat, wavelength, electric current, magnetic field, and more.

Measurement involves standard units. Thus length may be measured in feet, mass in grams, and time in days, for example. For uniformity, the scientific community has taken the *meter*, the *kilogram*, and the *second*, along with the *ampere* for electric current as the international system of units. Various instruments have been devised to measure all these.

(c) *Sensitivity enhancement type*: Our channels of perception respond to certain external stimuli by transforming them into experienced modes. Thus, oscillating air pressure may produce the sensation of sound, electromagnetic waves may create the sensation of sight, etc. However, all normal channels of perception have threshold levels. That is to say, stimuli have to be of a certain minimum intensity to experience them, i.e., become aware of them. Incidentally, the minimum threshold level for sound is not something to sneer at. The normal human ear can respond to sound energy of the order of unimaginably small amounts: Of the order of 10^{-16} watt. This corresponds to oscillations of amplitudes of molecular dimensions. Thus, if one whispers at too low a level, we may not be able to hear what is being said. An amplifying instrument will be helpful here. But we shouldn't complain. If the ear had been sensitive to weaker intensities of sound, we might have to endure the continuing noise generated by the slightest breeze, and many other vibrations that are continuously present in the world. The eye which is very sensitive to even very low energy photons also has a low threshold. Energy-wise, it is more or less the same as that for sound. We can't recognize a burning candle too far away from us because light from it which is reaching our eyes is far too faint. With the aid of a telescope this may be possible.

(d) *Sensitivity expanding type*: Our auditory and optical systems respond to pressure waves or electromagnetic waves only if the latter are within certain ranges. More exactly, only pressure waves within the range from 20 Hz to 20,000 Hz are audible to the normal human ear. But, with the aid of suitable instruments we can detect, study, and use pressure waves outside of this range too. Likewise, the normal human eye can detect as light only electromagnetic waves within the wavelength range from about 400 nm to 700 nm. But human-made instruments can detect, study, and utilize electromagnetic waves beyond this range. Such instruments have also revealed aspects of the universe of which we would otherwise be totally unaware. Dramatic instances of this are the elaborate radio-telescopes. These instruments have put into evidence the existence of certain radiations which come from every direction in the skies (the so-called isotropic radiation), and they have confirmed the correctness of the Big Bang theory of cosmogenesis.

(e) ***Detection of predicted results type*****:** Sometimes a theory in science might lead to the conclusion that a certain entity which has thus far not been recognized by the scientific establishment actually exists in the physical world. In such cases one devises new instruments (or makes a combination of previously known ones) to put into evidence the existence of the predicted entity. For example, in the nineteenth century J C Maxwell's theory established that there must be electromagnetic waves. One needed special instruments to put their existence into evidence. Many other theoretically predicted entities, like the neutrino and the omega minus particle of high energy physics, have been detected with the aid of suitable instruments. The interaction between theory and observation is at the very heart of the scientific enterprise, and instruments serve as a bridge between the two.

(f) ***Medical instruments*****:** To the above may be added instruments used primarily in the medical field to detect, analyze, or probe into matters relating to the human condition. Such, for instance, would be instruments like cystoscope, dioptometer, haptometer, and the myringoscope.

Historical Note

Instruments have been used since the most ancient times for the purpose of studying the world. Magnetic materials such as the loadstone were used for direction finding. Perhaps the first major scientific instrument, in the sense of a tool for observing the world, was the astrolabe. Used already by Eratosthenes of Alexandria in the 3rd century BCE, it is a simple device for marking the position of a celestial body at a given time and place in terms of its angular elevation from the horizon (Kathryn Lasky. *The Librarian Who Measured the Earth*, Little Brown, New York, 1994). It was improved upon and used extensively by Arab astronomers from whom it passed on to medieval Europe, as well as by Indian astronomers of later centuries (D M Bose *et al*, *A Concise History of Indian Science*, Indian National Science Academy, New Delhi, 1971). Tycho Brahe's voluminous data on planetary positions were collected with the use of astrolabes. They served as a springboard for Johannes Kepler's studies which, in turn, laid the foundations of modern astronomy (Kitty Ferguson, *Tycho and Kepler*: *The Unlikely Partnership That Forever Changed Our Understanding of the Heavens*, Walker and Co., New York, 2004).

But aside from the astrolabe, simple length and volume measuring devices as well as time reckoning contraptions to serve more practical needs, there were no instruments to measure the quantitatively defined features of the physical world until the 17th century. It was then that scientific instruments *per se* came to be invented.

The two most important instruments invented at that time, the telescope and the microscope, were not meant for any measurement, and both used the properties of lenses. These instruments have made us aware of the most massive and the most minute entities in the universe, the most far away and the most proximate entities too.

On the night of January 17th 1610, Galileo Galilei peered through his telescope and directed it towards the planet Jupiter. He thought he saw three faint stars in its vicinity. He was intrigued by this observation. He made it a habit to see Jupiter and the "stars nearby" night after night. Before a week was over, he spotted a fourth faint object. Galileo watched them patiently, and he made a great discovery: What he was observing were minor bodies revolving around Jupiter. When Kepler heard about Galileo's discovery, he thought of the Latin word *satelles* which means an attendant or a guard. So he suggested that these Jovian companions be called *satellites*. The name stuck for a long time. Galileo had made other interesting discoveries with his simple telescope, such as lunar mountains and the granular structure of the Milky Way (Albert van Helden, *Measuring the Universe*, University of Chicago Press, Chicago, IL, 1985). He presented all his astronomical findings in a slim volume which was entitled, *Sidereus nuncius* (Sidereal Messenger). It appeared in the year 1610. (Drake, Stillman, *Galileo: Pioneer Scientist*, University of Toronto Press, Toronto, 1990.)

The seventeenth century also saw the invention of an instrument that served both in the discovery of a new aspect of the physical world, and also in measurement: the barometer. (Knowles W E Middleton, *The history of the barometer*, The Johns Hopkins University Press, Baltimore, MD, 2002), More significant than the existence of vacuum was the conclusion from Torricelli's experiment that the atmosphere has weight. But if it has weight, and the atmosphere rises indefinitely, then wouldn't we all be crushed by it. Clearly, the atmosphere must extend to only a finite height. How can this be checked? By doing Torricelli's experiment up on a mountain. There the column of mercury in the tube would rise to a lesser height. This is what young Pascal did in 1648, comparing mercury heights in Torricellian tubes at Clermont-Ferrand and on top of Puy de Dôme. Sure enough, the column was shorter higher up, proving that the atmosphere gradually attenuates. There must indeed be an immense void beyond. A man and his brother-in-law carried troughs of mercury and thick glass tubes: one was at the bottom and the other climbed up a hill. The mercury level in the tube slipped down atop the mountain. That was all there was to it. And we came to know that the air surrounding us does not extend indefinitely!

The simple ruler is the first example of an instrument whose sole purpose is to measure. In the seventeenth century, two ingenious devices were introduced to measure extremely small thicknesses, of the order of a fraction of a millimeter: the Vernier and the micrometer. Today, through optical means, we can measure thicknesses with a precision greater than 10^{-20} m.

Another instrument of this kind was the simple pendulum which was useful for more precise measurements of time. This turned out to be extremely valuable in quantitative descriptions of phenomena which are among the fundamental factors that have made science so powerful. Quite unexpectedly, the simple pendulum was also responsible for the discovery of the slight flatness of the earth in the polar regions. (Maurice Daumas, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*, Portman Books, London,1989.) Common knowledge today, but arrived at only through tortuous routes.

The unraveling of the roots of perceived reality is a slow process, depending more on hard work, experimentation, and reasoning, and less on speculation, wordy argumentation, and sweeping statements about origins and ends. It requires ingenuity and intelligent observation. In retrospect, though, it all seems simple.

At about the same time, Otto von Guericke – lawyer, engineer, politician, and mayor of Magdeburg – invented an air pump (Friedrich Dannemann, *Neue 'Magdeburgische Versuche' über den leeren Raum,* Auflage Engelman Verlag, Leipzig, 1996). He used it to evacuate most of the air from a huge sphere made up of two tight-fitting hemispheres which could not be pulled apart even by the strengths of sturdy steeds because of the might of the atmosphere outside. Let us reflect on this a little: Though we move breezily through the earth's gaseous mantle, it in fact exerts a considerable pressure on us: to the tune of some fourteen and a half pounds on every square inch. This is equivalent to carrying a considerable load on our heads all the time. Perceived reality is bearable because of evolutionarily adjusted physiology.

There is more to vacuum than its recognition. In the course of time vacuum came to be used in refrigeration, in light bulbs, in cathode ray tubes, as well as in the manufacture of a great many things including thin films. Many scientific experiments require high vacuum, which is one reason why some day they may be conducted on the moon or in space because here on earth it is not easy to produce complete vacuum.

We are voyaging with the earth in the void of space, but within an airy film we call our planet's atmosphere. Transparent and unrecognized except when we reflect on it, invisible air is what sustains us as breathing beings. The gaseous sheath that encloses our globe is among the countless factors that make life possible on our planet. As Galileo said, "We live submerged at the bottom of an ocean of air." We see aquatic creatures and we can imagine plants and creatures at the bottom of the ocean. It does not occur to us that we ourselves are under a similar sea: not of water but of air. Instruments have opened our eyes to unsuspected roots of perceived reality.

It has been a long and unplanned trek from Democritan speculations about empty space and the Buddhist vision of shunya to the Torricellian recognition of some sort of ultimate emptiness. The leap from the speculative to the empirical modes of arriving at conclusions is significant. In all the clamor about science and non-science and claims that the ancients knew all about gravity and thermodynamics one tends to forget the fact that therein lies the essential difference between *modern* and *ancient* inspirations for constructing world views. That the atmosphere bears down on us with considerable and measurable weight is a fact of perceived reality that no amount of introspective intuition could have revealed.

More on Astronomical Instruments

Astronomy is the most ancient of all sciences. Human beings have gazed the skies and pondered about the stars since ancient times. Up until the seventeenth century, they relied mostly only on naked-eye observations of the heavens. What our ancestors achieved thus was quite impressive (Barry Hetherington, *A Chronicle of Pre-Telescopic Astronomy*, John Wiley, New York, 1992).

But after the invention of the telescope the most unexpected features of the celestial realm have come within our knowledge. Soon after the first discoveries of Galileo, and with improved versions of the telescope, we became aware of Saturn's rings, more satellites of other planets, double stars, star clusters, faint stars in well-known constellations, and much more. An entirely new planet, Uranus, was discovered in the eighteenth century, and two more, Neptune and Pluto, in the next two centuries. The first asteroid was recognized in 1801, then hundreds more. Eventually, with more and more powerful telescopes distant nebulas came to be known. In the twentieth century, even more distant galaxies were also found. From the detection of their mutual recession, the idea of an expanding universe emerged. (Peter Grego and David Mannion, *Galileo and 400 Years of Telescopic Astronomy*: to be published in 2010.)

Next consider the Hubble telescope, launched in 1990. Its defects were corrected by astronauts in 1993 (Robin Kerrod and Carole Stott, *Hubble: The Mirror on the Universe*, Fierefly Books, Tonawanda, New York, 2007). It is up there some 375 miles above the earth's surface. It has revealed the existence of super-massive black holes, given us clearer pictures of planets in our solar system, and of very distant galaxies too. The Chandra X-ray Observatory is another extremely complicated device which took pictures of Jupiter.

Radio telescopes are elaborately-constructed radio antennas. With their aid astronomers have registered microwaves emanating from distant sources, they have recognized strange new astronomical bodies, like quasars and pulsars. Radio telescopes have even detected what are believed to be the remnant radiations from the birth-pangs of our universe. Such have been the powers of astronomical instruments which continue to grow in sophistication and complexity. It is hoped that someday, we may even get a message from a distant civilization way out there! (Brian S McConnell, *Beyond Contact*: *A Guide to SETI and Communicating with Alien Civilizations*, O'Reilly Media, New York, 2001.)

None of these would have been possible without observational astronomy with the aid of telescopes which utilize little more than the properties of lenses and mirrors.

Microscopes

The first microscopes were also constructed in the seventeenth century, using simple lenses. Here too the ensuing discoveries were mind-boggling. The human eye is no doubt a marvelous instrument in itself. It transforms incredibly rapid oscillations of electromagnetic fields into hues and colors, forms and shapes, with the help of the brain of course. But it has its limitations. Things smaller than a minimum size simply cannot be recognized by normal human eyes. An entity the hundredth size of a dust particle cannot be recognized by the eye. What this means is that we may be surrounded by a billion micro-entities which are so small that we would never even know they even existed.

If we ask someone to list a dozen creatures at random, the list will probably include a few tame animals, a few wild ones, some birds and some insects, and possibly one or two that live in water. It is very unlikely that it would include any microorganism. This would certainly have been so before the invention of the microscope in the last quarter of the 17th century by the Dutch lens-grinder Antoni van Leeuwenhoek. (Alma Smith Payne, *The Cleere Observer*: *A biography of Antoni van Leeuwenhoek*, Macmillan, London, 1970.) Leeuwenhoek brought to our attention the existence of countless organisms that thrive and perish on a scale that is beyond our normal perception. He was also the first to detect spermatozoa in semen. When, in 1674, he presented his discovery of the plethora of organisms of unimaginable minuteness, the members of the Royal Society could not believe him.

Today it is common knowledge that stagnant water and the air around us, a spoonful of soil and putrid meat, all contain millions of bacteria. (Paul de Kruif, *Microbe Hunters*, Houghton Mifflin Harcourt, Wilmington, MA, 2002.) It is interesting to recall that almost two centuries after Leeuwenhoek's discovery, the scientific world thought that these animalcules were matters of mere curiosity. It was no doubt interesting to know that there is a whole new world of beings of insignificant dimensions beyond imagination. But they were treated like wild animals somewhere in the remote tundra of a far-off continent whose existence (apparently) has no effect whatsoever on ours.

Quite unexpectedly, it was discovered in due course that the existence of the invisibly small creature (microbes) is related to a great many diseases from which humanity suffers. But equally, the very survival of human beings is also dependent on a number of microbes. The ancients imagined that distant stars and planets affected human life, as do countless people even in the 21st century. It did not occur to anyone until the 19th century that these tiny creatures right here on earth affect human life in significant ways.

As with other instruments, the microscope also became more and more sophisticated with time, enabling us to see and record smaller and smaller entities. But here too there is a limit. The size of the smallest objects that may be identified as separate units by means of a microscope will be determined by the wavelength of the light used. This fact is utilized in electron microscopes which utilize the wave property of electrons: the waves associated with electrons being much smaller than ordinary light waves, one can detect significantly smaller things by using electron microscopes; or, as one says, electron microscopes have a higher resolving power than optical ones.

Dials and Calibrations

Measurement is the lifeblood of science. (Herbert Arthur Klein, *The Science of Measurement: A Historical Survey*, Dover Publications, New York, 1989) In antiquity, time was reckoned during the day by observing the length of the shadow of a vertical pole held in sunlight. Such a device came to be called a dial (from the Latin word *dies* for day). A very ancient reference to this is found in the Bible where we read: "Behold, I will bring again the shadow of the degrees, which is gone down in the sun dial of Ahaz, ten degrees backward…" (Isaiah: 38.8)

Many centuries later, when numbered clocks became common, the face of the clock came to be known as a dial. Later still, when other measuring devices were invented with pointers to read the measurement, their faces were also called dials. Today, there are countless dials in the world of science and technology which tell us at a glance the measure of a physical quantity.

Originally the word *calibre* referred to the bore of a gun. Fairly accurate uniformity and measurement of this bore was essential for gunnery and warfare. Later, the term came to be used for the bore of any tube, as of a thermometer. In modern usage, the term calibration refers to the accurate marking on any measuring device which will enable the user to read the precise value of the measured quantity with respect to a standard that has been set by the scientific community.

Thus, calibration of a scientific instrument implies that there is a well-defined standard of measurement for the corresponding quantity. Here, as in practically every aspect of the scientific enterprise, the international nature of science becomes clear. By mutually agreed upon conventions, there are well-defined units for every physical quantity that has been defined: from length, time, mass, and electric current to numerous other quantities.

All ancient cultures had their units of mass and length and time. To get an idea of how sophisticated science has become in modern times, consider the unit of time in the international system: the *second*. It is defined as the duration of 9,192,631,770 (9 billion, 192 million, 631 thousand, 770) periods of the radiation from the transition between two hyperfine levels in the ground state of the cesium-133 atom.

Barely two centuries ago, the meter was defined as a millionth part of the longitude from the equator to the North Pole, passing through Paris. Today, the unit of length is still the meter, but it is defined as the distance traversed by light in vacuum in 1/299, 792, 458 of a second.

For the unit of mass, there is an international prototype which is taken to be a kilogram.

The international unit of electric current is known as the ampere which is defined in terms of the force that such a current in a wire of negligible cross-section would exert on a very similar wire carrying an equal amount of the current, placed at a specified distance from each other in a vacuum.

It is important to realize that when scientists talk of the quantitative features of the world, they refer not only to the measurable aspects, but, more importantly, to the specific values that these have under given conditions. Sometimes, the minutest differences from the expected values could lead to significantly new insights and/or theories.

Magnetic Compass and Electroscope

Magnetic properties were known in ancient China and Greece. The magnetic needle pivoted in a compass enabled one to locate positions and determine directions. Like our eyes and ears which serve our needs quite effectively, whether or how well we understand how they function, the compass was an instrument which served a purpose long before its underlying principles were clearly understood.

Though electrically-induced phenomena had been observed even in ancient times, it was only in the 17th century that they came to be recognized as resulting from a specific feature of the physical world called electricity. William Gilbert, one of the early investigators of electrical and magnetic phenomena in the modern world, introduced an instrument which he called the *versorium* which was the first instrument that put into observational evidence the existence of electric charges. (William Gilbert, *De Magnete*, 1600, Basic Books, New York, 1967) .

The Spectroscope

In the first decade of the 18th century Newton reported that white light is a combination of several color lights, a simple observation anyone can make today with the aid of a prism. A little over a century had to pass by before the instrument we now call the spectroscope was invented. It is one of the most valuable instruments in the arsenal of the experimental scientists. Basically the spectroscope consists of just two tubes, a prism, and a circular plaque on which degrees are etched. Light from a source enters the first tube and is split into its component parts by the prism. By adjusting the second tube, one observes the different components, and the marked degrees enable us to determine the angles through which the various split lights have emerged from the prism.

Theory shows how these angles are related to the wavelengths of light. Thus, for starters, the spectroscope enables us to determine the wavelengths of colored lights. But there is more: It turns out that different hot sources give out radiations of different wavelengths which are characteristic of their chemical composition. Thus, for example, if the source contains calcium, certain wavelengths will be emitted; if it contains, certain other wavelengths will be given out. In other words, the wavelengths are a kind of signature for every element. (J F James and R S Sternberg, *The Design of Optical Spectrometers*, Chapman and Hall, London, 1969).

This is a most valuable discovery because by analyzing the light from a source we can know its chemical composition. This fact at once opens up the possibility of knowing the composition of the sun and of other distant and unreachable bodies in the sky. It is no mean accomplishment to be able to discover that the sun has iron in it or that another star contains magnesium. Yet, this is what we have been able to do with the aid of spectroscopy. It was through the spectroscope that the element helium was discovered, first in the sun (Clifford A Hampel, *The Encyclopedia of the Chemical Elements*, Reinhold Book Corp, 1968). Also, from the precise measurement of the radiations scientists can know whether the source is stationary or moving away from or towards us. In other words, spectroscopy can also reveal the motion of the stars and of galaxies. In fact, the recession of the galaxies and the expansion of the universe could never have been known without the aid of spectroscopes.

Then again, when light from a hot hydrogen source was carefully analyzed in a laboratory, it was found the specific wavelengths emanating from it had a pattern to them: that is to say, the numbers were not random, but related to one another in a specific way. This puzzle was resolved by a theory which envisaged the atom to be made up of a central core (the positively charged proton) and an orbiting (negatively charged) electron. This was a discovery of major proportions: atomic theory has its roots in the spectroscope.

Aside from visible light, there are other radiations too, such as gamma radiation, X-rays and ultra-violet to infra-red, microwaves, and more. With the aid of spectroscopes and radio-telescopes, we have been able to detect these two from outer space.

Thus we see that the spectroscope has brought us knowledge and understanding about the physical world from the minutest realms to the farthest recesses of the physical universe.

Twentieth Century

Among the major achievements of the twentieth century one should mention the extraordinarily sophisticated instruments that were invented during its course. These instruments have revealed to human understanding a most impressive range of entities from the minutest entities to the farthermost recesses of the physical world, and a great deal in between.

We could never have known about the existence of galaxies, let alone their speeds of recession without the telescopes of the twentieth century. The physical reality of hypothesized atoms and nuclei has been established by means of new instruments. The structure of complex molecules, including the ones which are the very basis of life, has been brought to light by means of other instruments.

A plethora of sub-atomic and sub-nuclear particles as well as their many properties have been put into evidence, thanks to various particle accelerators. To get some idea of the complexity of some of these modern instruments, consider some of the vital statistics of the Tevatron at the Fermilab (Fermi National Accelerator Laboratory), not far from Chicago, Illinois. (Frank Close, *The New Cosmic Onion*, Taylor & Francis, New York, 2006). The Tevatron is a huge accelerator buried underground, in ring form, whose diameter is 2 km. It embodies two thousand electromagnets. Protons are accelerated through these rings until they attain speeds of 300 million meters a second and have energies of the order of one trillion electron volts. When such high energy protons strike metal targets, all kinds of elementary particles splinter into existence. There are similar statistics for the Large Hadron Collider at CERN: with a circumference of more than 26 km, and with 9300 magnets, cooled to –193.2°C. It uses more than 10,000 tons of liquid nitrogen and 60 tons of liquid helium. (http://lhc.web.cern.ch/lhc/)

Then again, we have instruments that can measure the wavelength of radiation with a precision of about 10^{-21} m. Likewise, masses can be measured with extremely sensitive instruments to a precision of a trillionth part of a kilogram. As one author puts it, this is equivalent to be able to measure the amount by which an ocean liner weighing several thousand tons would sink when a fly lands on it.

Concluding Thoughts

The point to remember, especially by those who speak lightly of science's claims to knowledge, is that little of coherent, measurable or practical value can be achieved concerning the physical world without scientific instruments. Instruments are to science what eyes and ears, nose and taste and touch are to the human body: it is through them that we become aware of the world. They also serve as extensions of the faculties of perception that nature has endowed us with. It is through them that we discern the world both qualitatively and quantitatively from the microcosm to the very limits of the universe. The mind alone can only reflect, it is only with instruments that it can measure. Speculation, philosophy, and metaphysics have roles to play in human culture because they are interesting and fulfilling too, but in entirely different contexts.

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