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Wonder and knowledge: scientific investigation and the breadth of human reason

Marco Bersanelli

Dipartimento di Fisica, Università di Milano, Via Celoria 16 - 20133, Milano, Italy
Marco.Bersanelli@fisica.unimi.it

Abstract

Science is usually perceived as the result of a powerful and rigorously defined method based on experiment and logical-deductive reasoning. While such synthetic description captures a central aspect of the scientific method, a broader range of cognitive factors is actually at work in the process of scientific research. Clearly, human reason is not limited to those intellectual features that are considered typical of science. Entire intellectual enterprises such as philosophy, theology, history, music, art, or basic forms of discernment essential to our existence such as trust, understanding of personal behavior and human relationships are clearly not irrational approaches, yet they engage our reason according to ways that are different from, and that appear irreducible to, those typical of science. A closer look at the workings of reason in research suggests that a blend of rational and affective elements, more complex and interesting than normally assumed, are relevant to the enormous success of science. What human capacities play a role in scientific discovery? What intellectual elements are actually at work when we, as scientists, carry out our research? This is connected to another key question: What kind of conclusions can scientists hope to draw as a result of their investigation? What level of truth can they claim to achieve?

1. Introduction

Science is usually perceived as the result of a powerful and rigorously defined method based on experiment and logical-deductive reasoning. While such synthetic description captures a central aspect of the scientific method, a broader range of cognitive factors is actually at work in the process of research. Clearly human reason is not limited to those intellectual features that are considered typical of science: our rationality is capable of a wide spectrum of methods appropriate for different forms of knowledge and creativity [1]. Entire intellectual enterprises such as philosophy, theology, history, music, art, or basic forms of discernment essential to our existence such as trust, understanding of personal behavior and human relationships, are clearly not irrational approaches, yet they engage our reason according to ways that are different from, and that appear irreducible to, those typical of science. Human reason is versatile, agile, and capable of gaining genuine new knowledge through a variety of methods (see chapter 2 in [2]) depending on the type of object we seek to know and the kind of question we ask.

On the other hand, we do not perceive our reason as fragmented into rigidly separated compartments, rather as a whole capable of expressing itself in different modes. Nor do we perceive our reason as separable from our affective dimension. There is no way for us to begin a cognitive process, or to appreciate the relevance of a result we have obtained without the participation of our affective domain: we desire to know an object when it strikes us as interesting, and we are touched and changed by a new comprehension we may have achieved. Every cognitive process involves the entirety of our person: reason and affection. As we shall see, scientific knowledge is no exception. In fact, a closer look at the workings of reason in research suggests that a blend of rational and affective elements, more complex and interesting than normally assumed, are relevant to the enormous success of science. What human capacities play a role in scientific discovery? What intellectual elements are actually at work when we, as scientists, carry out our research? This is connected to another key question: What kind of conclusions can scientists hope to draw as a result of their investigation? What level of truth can they claim to achieve? To guide our path in exploring the use of reason in science, it will be useful occasionally to consider the experience of eminent scientists directly involved in the battle of research, rather than insist on second-hand principles or a priori assumptions.

2. The breadth of reason

There is no such a thing as a part-time scientist. People involved in scientific research find themselves fully committed and animated by a deep emotional component. Great scientists may have the most diverse personalities, but they are all in love with the mystery they seek to grasp. Albert Einstein, praising Max Planck in the occasion of his sixtieth birthday, claimed that [. . .] the state of mind which enables a man to do work of this kind [Plancks scientific achievements] is akin to that of the religious worshiper or the lover; the daily effort comes from no deliberate intention or program, but straight from the heart [3]. Where does such a profound involvement originate? What maintains the high dedication of so many researchers throughout a life time? While every single step of a scientific investigation is based on rigorous quantitative evaluation, most scientists agree that a major source of their motivation rests on aesthetic and affective grounds.

2.1 The role of aesthetics and affection

Addressing the relevance of an affective component in science has nothing to do with an idyllic feeling about nature; rather it means to recognize the non-obviousness of the existence of a cosmic world that precedes us and calls us to unveil its secrets.

2.1.1 The starting point

There is a deep emotion for the very fact that reality *"is"*, that triggers our mind to search for a meaning. This is the foundation of any cognitive attitude. The initial fascination of a scientist, just like that of an artist or of a philosopher, is rooted in the elementary astonishment for the mere presence of things. The scientific spirit is particularly inflamed by the intuition of an orderly structure in the physical world and is deeply attracted by the possibility of gaining some insight into such order. This could be expressed as the intuition of the cosmic nature of the physical world.

Such intuition is at the basis of the positive intellectual attitude that is needed to initiate the adventure of science. The belief that an understanding of the universe is possible and worthwhile is at the beginning of the process [4, 5]. However, such primordial wonder is not just a good initial motivation. In science, every phase of the investigation (observation, experiment, hypothesis, discovery, verification) is ultimately sustained by the awe for what is, and each step has an element of attractiveness within it.

2.1.2 The attractiveness of nature

The original wonder for the presence of things is enhanced by our sensitivity for the beauty of nature. While a definition of beauty, even within the particular context of the natural sciences, is highly elusive, it is impossible to deny the importance of aesthetics as a source of interest, curiosity and desire to understand natural phenomena. The admiration and fear for the night sky felt by ancient observers, for example, was certainly a key for the beginning of astronomy and of science at large. We can only vaguely imagine the deep wonderment of early humans, say half a million years ago, gazing at the mysterious light of the stars and at the silver wake of the Milky Way in the complete darkness of prehistorical nights [6]. Since then, some twenty thousand generations have contemplated the same majestic scenery — only the last couple of them have nearly lost that experience due to light and atmospheric pollution.

How did the aesthetic appeal for some natural realities establish itself in our minds? This question —still largely unanswered— has challenged philosophers, psychologists, biologists for a long time. It has been suggested that it may be, at least in part, the result of an evolutionary adaptation process. Those landscapes that were safer and therefore more likely conducive to survival for our ancestors, such as a panorama from a hilltop or an open view on a savannah environment, might have been preserved in successive generations as entangled with a sense of positivity and comfort [7, 8]. Aesthetic preference might also have been developed for those views that invite to explore new territory, probably a life-enhancing element for early nomad human groups [9, 10]. Perhaps our deep attraction for the night sky falls into this category. But whether or not we understand anything of its ancestral origins, our aesthetic sensitivity undoubtedly supported, through millennia, increasingly rigorous observations of the sky, of the motion of celestial bodies, and of a wealth of other natural phenomena.

Aesthetics is not just relevant for the initiation of mankinds interest for nature millennia ago: a similar dynamics is at work today. I know very few professional astronomers who were not led into the field by some form of profound attraction for the sky or celestial objects in their youth or childhood (interestingly, seduction for science often sets in at very young age). I believe that this situation applies not only to astronomy, but it is common to all fields of fundamental science. As Henri Poincar stated, scientists do not study nature because it is useful. They study nature because they enjoy it; and they enjoy it because nature is beautiful (Poincar, quoted in [11]).

It is not just a matter of getting excited with some highly unusual phenomena. The ability to recognize as non-obvious and to perceive as fascinating the physical behaviour of nature in its ordinary aspects (a rock falling under gravity, the spherical shape of the Sun, the darkness of the night sky) is a clear sign of our sensitivity to natures hidden harmony. Those who feel no surprise in looking at the profile of the moon wont be really touched even by the paradoxes of black holes.

2.1.3 Embarrassed by beauty?

As a consequence of a deep-rooted erroneous mentality, scientists are supposed to be affectively detached from the object of their study. However, this is a dangerous form of self-deception, as Konrad Lorenz stated [12], and it turns out to be an attitude quite unknown in the real life of researchers. If a scientist were to strictly follow the theorized affective indifference for the object of her/his study, her/his research would probably be stuck at the starting blocks. Some authors admit that a sense of personal involvement comes into play, but this is often regarded as an unimportant, or even dangerous, emotional byproduct of our otherwise rational minds. On the contrary, the testimony of several scientists shows that wonder and beauty play a decisive role, probably as essential to scientific creativity as the use our logical skill (see Chapter 1 and Chapter 6 in [13]). The great physicist Max Planck once remarked that those who have reached a stage where they are unable of wonder for anything, simply demonstrate that they have lost the art of thought and reflection". Here wonder is not seen as a juvenile imperfection that will vanish as we fully develop our scientific attitude; on the contrary, it is judged to be as indispensable to move our reason as fuel is to run a well designed engine.

In the context of our understanding of the universe, cosmologist Mario Livio suggested [14] to introduce a Cosmological aesthetic principle, simply meaning that any fundamental theory of the universe must be beautiful according to some aesthetic guidelines. He quite appropriately points out that: A close examination of the history of physics and cosmology reveals [. . .]

that physicists have in fact adopted this principle wholeheartedly and it is only its name that [. . .] has not been formally spelled out. While a general agreement on the definition of the aesthetic canons of a cosmological theory is difficult and probably destined to remain open, the recognition in the history of science of a constant underlying aesthetic guidance is inescapable. As Steven Weinberg once pointed out: We believe that, if we ask why the world is the way it is and ask why the answer is the way it is, at the end of this chain of explanations we shall find a few simple principles of compelling beauty [15]. If the famous tenet of the fathers of the Church, *pulchrum est splendor veritatis*, has anything to do with the real world, then we should not be surprised that aesthetics turns out to be a useful guide also in the context of modern cosmology.

2.2 The many faces of beauty in science

2.2.1 More knowledge, more wonder

It is a diffused opinion that the advancement of science coincides with the inexorable retrocession of the sense of beauty and mystery. But the experience of those actually engaged in research shows exactly the opposite. A more profound scientific explanation of a phenomenon does not suppress our sense of wonder, but enhances it: a circumstance that further indicates that an aesthetic dimension is finely intertwined with, and inseparable from, scientific enquiry. Anyone actually working in science will feel a resonance with these words of physicist Carlo Rubbia [16]:

> *When we look at a particular physical phenomenon, such as a night sky full of stars, we find ourselves deeply moved, we perceive a message that comes from nature that transcends and dominates us. This same feeling of amazement, wonder and respect that we experience when contemplating a natural event, is felt much more profoundly by scientists, i.e. by the experts, those who see the phenomenon from the inside. The beauty of nature, as seen from inside and in its most essential terms is even more perfect than it appears from outside.*

The appreciation of the beauty of a rainbow is by no means diminished by the knowledge of the delicate combination of physical circumstances that make it happen: on the contrary, scientific understanding will introduce the awareness of a surprising underlying order behind it; this in turn will allow to recognize further subtleties —such as secondary arches, additional colour gradations, correlated change in luminosity, etc.— enriching the beauty of our vision of the rainbow [17]. New knowledge is also the source of motivation and cognitive energy for further investigation. As the great physicist Richard Feynman remarked [18]

> *The same emotion, the same wonder, the same mystery are born again every time we look at a given problem in a sufficiently profound way. A greater knowledge always comes with a more unfathomable and wonderful mystery, that leads us to penetrate even more deeply.*

As science proceeds, we are brought to new vista points onto reality and we are more exposed to the beauty of creation. Admittedly, however, this is not the typical perception. The idea that surrounds progress in science is rather a growth of meaninglessness and disillusion, breaking up with an ancient world where passion and contemplation used to be possible. Perhaps the problem is that, in order to enjoy the panorama, it is not enough to stand at a mountain top. One needs to pause and look around, and to be open to the possibility to recognize unity and meaning in the surrounding world.

2.2.2 Changing ground under our feet.

The normal way in which a dimension of wonder and awe for nature is preserved and enhanced by the progress of science is the inherent property of new discoveries not to simply answer questions, but to widen the grounds on which those questions where initially posed. New understanding opens up new facets of reality, previously unimagined, with their own attractiveness and unsuspected depth. Probably every single fundamental issue about the universe posed in ancient times, and that has become subject matter of modern science, has received a new and deeper dimension of mystery precisely from the new knowledge that science has brought in. Several examples can be made, but a hint to a couple of cases will be sufficient here.

Ultimate bricks

The big question of what are the ultimate constituents of matter goes back to the great philosophers of ancient Greece. Among their most fruitful ideas were those proposed by Empedocles of Agrigentum and later developed by Leucippus and Democritus in the fifth Century BC, who postulated that all matter is made of atoms, indivisible and indestructible particles moving in a perfect void. The observed changes of macroscopic objects was ascribed to the rearrangement of such ultimate particles. They imagined that atoms, immutable in time, could be of different kinds and shapes and their collisions were ruled by pure random processes. Throughout centuries the atomic theory gained credibility but lacked direct observations. It was only in the late nineteenth Century that experimental tests could be made. While the ancient idea of pure randomness in the interactions was to be contradicted by the modern discovery of well defined physical laws governing the microscopic world, the basic intuition of the existence of atoms turned out to be correct. Today the existence of atoms is a matter of fact. Our understanding confirms some of the ancient intuitions: atoms come in different types, are all identical within a given kind, and their combinations support the evolution and variety of the macroscopic world. However, today we know that atoms are far more complex systems than what the ancient philosophers imagined. The story is well known. Ernest Rutherfords discovery of the large angle scattering of – particles demonstrated an atomic structure with a dense core and external electrons with opposed electric charges. Protons, neutrons and electrons were then recognized as more fundamental particles than atoms themselves. But that was only the beginning of the shift.

A wealth of other sub-atomic particles were soon discovered, most of which turned out to be highly unstable. The interactions between particles is not random, but subject to four basic forces: electromagnetic, weak and strong nuclear forces, and gravity. Today, a new set of fundamental particles has emerged as the latest incarnation of the ancient atomistic paradigm: physicists identify two families of six particles each, quarks and leptons, depending on whether they are sensitive or not to the strong nuclear force. But an even more dramatic change has happened in the meantime. The understanding of the very concept of particle has been supplanted forever by quantum mechanics. As we approach the microscopic realm, the way we describe basic physical features such as position and speed, time and energy does not correspond to our intuition. The idea of an ultimate indivisible material element has been replaced by the more ineffable concept of a particle-wave dual reality. We have been lead to surpass our common sense on fundamental concepts such as space, time and identity. Fortunately, while our intuition breaks down, mathematical language still guides us safely [19]. Twenty-five centuries after Democritus, modern science reached an unbelievable depth into the intimate nature of matter. However, not only there is no conclusive answer on what are the ultimate ingredients of matter, but by questioning the very concept of particle the ground of the ancient question has been moved into new, uncharted territories.

Black depth

As a second example we go back to the night sky, full of stars. Today we know things about stars that early observers could not even imagine. Physics has enabled us to understand in great detail the structure and evolution of stars, from the smallest and longest-lived to the brightest and fugacious ones. We can compute in great detail the outcomes of nuclear reactions responsible for the production of energy in their interiors. We understand the large scale evolution of stellar populations within galaxies. Recently, astronomers have produced accurate maps of star distribution within our galaxy thanks to the combined results of high precision astrometry and optical and infrared space observatories. Has all this knowledge diminished our enchantment for stars? Are we left with a disappointing and perfectly working set of empty mathematical formulae? That is certainly not the case. And, more remarkably, what astronomers have unveiled about the physical workings of stars has introduced entirely new perspectives that would not be thinkable otherwise. Consider the question: why does it happen that nuclear reactions in the core of stars are so precisely tuned to form the heavy elements necessary for life to emerge? Our very ability to pose such a question rests on a monumental pyramid of patient astrophysical work carried out through several decades. A question like that is highly relevant in both scientific and metascientific contexts, and suggests us to look with novel eyes at the relationship between the laws of physics and our own existence.

Lets go back to our night sky. Modern cosmology has revealed an amazing significance of the dark background of the sky that ancient observers failed to notice precisely for their lack of scientific insight. Generations of pre-scientific observers have wondered about the nature of the stars. But what about the all-encompassing black background? Today we know that it corresponds to the so-called last scattering surface, the space-time region from which we receive a uniform and feeble fossil light from the early universe. Such primordial radiation, the cosmic microwave background, has travelled for 13.8 billion years before reaching us. During the long journey its wavelength was streatched by a factor of 1000 by the expansion of the universe. As a consequence, the energy of the ancient light that reaches us today is extremely weak, giving us the appearence of a black background. Where does the radiation come from? The expansion of space has the effect of bending-in the past light cone at large distances: beyond a certain point, concentric spheres at increasing radius around us become smaller and smaller and converge around a point at the origin of space-time. Therefore looking up at the sky in any direction literally means to look towards a single point near the origin of the universe [6]. Today, a person educated in cosmology contemplating the sky in a clear night can enjoy the thought that the entire dark background is a direct signature of the origin of the universe: it is a new possibility of aesthetic experience brought in by scientific insight. Something perhaps too fantastic even for the fantasy of ancient thinkers.

2.2.3 Simplicity.

Physicists have an irresistible attraction for the simplest possible description of nature, for laws that involve minimal sets of concepts and that are capable of explaining a large variety of phenomena apparently independent of each other. The noteworthy property of nature of being legible, in spite of its complexity, in terms of relatively simple laws is the source of secret fascination for a scientific spirit. If simple laws were to correspond to a very limited set of outcomes, then no surprise; and if a great diversity and richness of physical phenomena required a similarly complex set of underlying laws, then no wonder. It is the contrasting combination of the simplicity of the underlying laws and the breathtaking diversity of physical realisations that strikes us as a deep element of beauty in nature.

While simplicity is a sure aesthetic canon in science, it does not easily translate into a quantifiable measure. As Steven Weinberg pointed out, Newtons theory of gravity is described by three equations while Einsteins general relativity requires fourteen: but this should not be regarded as an aesthetic advantage for Newtonian gravity. Its not just a matter of minimising some measure of the syntax used in the mathematical language required by the theory; rather, it is connected with the synthetic power of the central idea that describes a behavior of nature. The beauty of a physical theory rests on a sense of proportion and inevitability. Like a perfect artwork or a piece of music, every detail is just where it should be in the context of the whole, and we would not want to change anything in it.

2.2.4 Symmetry.

Symmetry is a concept strictly related to that of order, indeed an essential ingredient of our perception of beauty in nature. In the context of a physical theory, symmetry is an expression of the invariance of the physical laws under certain transformations, such as translation, rotation, time, etc. Such invariances are at the origin of natures orderliness and lead to fundamental conservation principles, such as conservation of linear and angular momentum, or conservation of energy.

But order and symmetry left to their own and pushed without limit may rapidly lead to immobility and featurelessness. Total symmetry is found in total absence of structure. What we see in our universe is profoundly different. The laws of nature give rise to a world rich with structure and fertile with events. The more we understand the history of the universe the more we witness a sequence of authentic novelties at cosmic level, emerging from previous conditions yet irreducible to them. Consider the first formation of atoms, about 380,000 years after the big bang: at that time the energy density became low enough to allow electrons to join the protons and light nuclei: suddenly, and for the very first time, an immense new range of physical processes and possibilities was realised. Transitions of this sort can be described as successive breaking of symmetry, starting from a situation of maximal symmetry in the very early universe and decreasing as a result of cosmic expansion. Nature blossoms in its beauty and diversity from a delicate interlacing of symmetry and symmetry breaking, of laws and unpredictable events, of order and chance.

2.2.5 Chance and order.

Often our attitude towards the concept of casuality is dominated by an impression that chance dwells at the opposite pole from any coherent character of nature. Chance is often mentioned as a synonymous of meaninglessness: when we state that a given fact is fortuitous we often conclude that it has no particular meaning. I find this rigid mental bond between chance and lack of meaning rather strange, since it is abundantly contradicted by our experience. Often some of the most meaningful and far-reaching events in our personal existence, such as the encounter with a key person in our life, happen in a radically unpredictable way.

Up to the early twentieth Century, scientific progress assumed that casuality is an illusion and that nature is in fact completely controlled by rigidly deterministic laws. In such an entirely mechanistic world there seems to be no place for true novelty and hardly an openness to meaning. But ever since modern physics has introduced an unavoidable element of unpredictability, particularly through quantum mechanics, we have come to realise that only a fine combination of deterministic laws and an appropriate dose of chance can create the condition for an interesting and beautiful universe. Chance and order: both collaborate to the aesthetic dimension of nature as we know it. Nature offers to us a feature that may be even more elegant and fruitful than the stability of the laws of nature on one side, and the novelty of unpredictable events on the other: the indissoluble unity of the two. Perhaps both chance and order need to be understood as manifestations of a deeper reality.

3. Science and truth

3.1 Human reason and scientific method

3.1.1 A dialogue with the universe.

When a child is attracted by something special that he has seen, his natural response is to open his eyes wide and move towards the object to see it more closely, perhaps attempt to seize it. Similarly, for a scientist who got interested in some phenomenon, the first methodological step is a careful observation of the object. A more sophisticated case of observation is a selective process by which we limit and simplify what we can observe in order to obtain better defined answers: an experiment. In science, observation and experiment follow naturally our being attracted by a given phenomenon: in absence of this move, the initial aesthetic impact will not conduce to a scientific process – perhaps it will lead to another cognitive path. In a general sense, observation is relevant not only for the experimental scientist, but also for the theoretician: there is a very real sense in which a new idea, once it has entered our mind, needs to be observed, considered from different angles, looked at.

Observation in science is far from being an obvious capacity. According to Alexis Carrel, to observe is less easy than to conjecture and think, since as everyone knows, few observations and much discussion are conducive to error; much observation and little discussion, to truth" [20]. Here Carrel does not mean, of course, that reasoning is bad for scientific understanding; rather, that any sound scientific thinking needs to be constantly subdued to the reality of the facts as disclosed by observation. Our scientific reason begins with how we look at the data in front of us: it is essential how we use our eyes. Interestingly, our retina is indeed a portion of the brain that has evolved to be physically exposed to the outside world, like a cerebral extension set out to receive external inputs as directly as possible.

Observation requires us to be free from prejudice. While an initial hypothesis is a necessary prerequisite of any meaningful observation, an excessive attachment to our ideas leads to distortion or intellectual blindness. Claude Bernard is reported to have said: Men who have excessive faith in their theories or ideas are not only ill-prepared for making discoveries, they also make poor observations (Bernard, quoted in [21]).

Observation and experiment are our ways to question the universe. By them we hope to obtain answers suggestive of some hidden features — empirical regularities, quantitative laws, etc. Therefore, conceiving an observation or an experiment involves rational processes that are similar to our ability to formulate questions. When we design an instrument for a new astrophysical observation, for example, such as a complex space-based detector, we use our creativity to reach the extreme sensitivity needed to detect the tiny signals we are after while maximising the simplicity of the hardware and observing strategy. An instrument is very much like a materialised version of a set of questions that we ask, so to speak, to the universe itself: How intense is your radiation here and there? How much energy do you have at different wavelengths? As in human communication, in order to get useful answers our questions must be well formulated and simple, possibly admitting univocal or highly focussed feedback. Rejecting unnecessary complications in the experimental set up is analogous to avoiding superfluous words when we cry out an important question to somebody far from us in a noisy background.

3.1.2 Like a wonderer on the mountains.

No handbook on the scientific method will tell you how to design a new instrument. Similarly, the formulation of a new hypothesis or a novel theoretical interpretation is not the consequence of a predefined procedure. Intuition, inventiveness, imagination, rather than logic, assist scientists in finding the entrance to a new path. As Einstein wrote: There is no logical way to the discovery of these elementary laws. There is only the way of intuition, which is helped by a feeling for the order lying behind the apparence [22]. Even in the field of mathematics intuition often anticipates a rigorous demonstration. Gauss said, referring to a theorem on which he was working: I have the result, but I still don't know how to get there (Gauss, quoted in [21]). The formulation of an idea does not coincide with a deliberate, voluntary act: it is something that happens to us rather than something we do, to the point that when it happens we are the first to be surprised. Only the interaction with a master, i.e. someone who has gone through the whole process before us, can be a great help in gaining the familiarity with a proper fruitful approach.

Scientific investigation proceeds through careful planning and systematic analysis. However, anyone with direct research experience knows that the success of the work is always partly out of our hands. The great biologist Theobald Smith observed that discovery happens like an adventure rather than as the result of a logical process of thought. Acute and lengthy thought is necessary in order to stay on the path, but it doesn't necessarily lead to any discovery [23]. In 1831, in a letter to a friend, Michael Faraday wrote: I am busy just now again on electromagnetism, and think I have got hold of a good thing, but cant say. It may be a weed instead of a fish that, after all my labour, I am at last pulling up (Faraday, quoted in [21]). The dawn of a discovery often comes after a long night and a slow twilight. Albert Einstein, recalling his troubled intellectual path leading to his theory of relativity, wrote: These were errors in thinking which caused me two years of hard work before at last, in 1915, I recognized them as such... The final results appear almost simple; any intelligent undergraduate can understand them without much trouble. But the years of searching in the dark for a truth that one feels, but cannot express; the intense desire and the alternations of confidence and misgivings, until one breaks through to clarity and understanding, are only known to him who has himself experienced them [22].

There is always an element of surprise in the experience of discovery, as though reality, conquered by our attempts, finally yielded up to us something of itself. Ingeniousness and tenacity are indispensable, technological advance is decisive, the ability to coordinate large research groups is increasingly important in great experiments like particle accelerators or space missions. And yet in no case is scientific discovery purely a consequence of the work done. It is rather the vision of a new landscape that we have the privilege of admiring from the vantage point we have gained through a combination of hard work and favourable circumstances. In some strange way, any new fact or insight that I may have found has not seemed to me as a discovery of mine, but rather as something that had always been there and that I had chanced to pick up [11], said astrophysicist Subramanyan Chandrasekhar.

Not just any account of a new phenomenon is a discovery, but only where it introduces some new understanding in our horizon. The great physicist and mathematician Hermann Von Helmholtz has described in the following terms [24] the most exciting phase of his scientific work:

> *I am fain to compare myself with a wonderer on the mountains who, not knowing the path, climbs slowly and painfully upwards and often has to retrace his steps because he can go no further — then, whether by taking thought or from luck, discovers a new track that leads him on a little, till at length when he reaches the summit he finds to his shame that there is a royal road by which he might have ascended, had he only had wits to find the right approach to it. In my works, I naturally said nothing about my mistake to the reader, but only described the made track by which he may now reach the same heights without difficulty.*

Interestingly, only when we find a comprehensive answer are we able to make sense of the forest of hypotheses, initial attempts, intuitions that lead us through the path. In light of that answer we can finally formulate the clear questions, of which those we had asked at the beginning were only poor approximations.

New discovery reawakens our desire to know, it recreates the sense of possibility, it marks a new beginning. There seems to be no end to the richness and depth of the physical world we try to understand, as every answer coincides with a new, deeper question. Tyndall, in describing the work of Faraday, noted that: Knowledge once gained casts a faint light beyond its own immediate boundaries. There is no discovery so limited as not to illuminate something beyond itself [25].

Finally, discovery is always accompanied by a feeling of gratitude and joy. Claude Bernard has written that the joy of discovery is certainly the liveliest that man's mind can feel, and Pasteur echoes him, when finally one achieves certainty, his joy is one of the greatest perceived by the human soul (quoted in [21]). If the step of discovery were an automatic outcome of our effort, this joy would not be explained. But perhaps the origin of this gratitude does not lie so much in the pleasure for a discovery per se, as much as in the perception of a mysterious link between ourselves and the universe that every discovery evokes. What makes us able to understand nature?

3.1.3 The miracle of physics

There is no *a priori* reason for why our minds should be granted with the ability to understand the universe to the level it does. We expect that evolutionary processes shaped our mental structure for survival, favouring an ability to foresee and understand natural phenomena connected to our direct experience. This is realized with remarkable effectiveness in all complex animals, each in their own environment, with a variety of ingenious neuro-biological solutions. Humans, in addition, have developed a mathematical language, i.e. the ability to create and use logical structures according to a pattern somehow encoded in their brain. This is of course an impressive achievement in itself, but the surprising element is that such language turns out to be adequate to describe the physical universe to the limits of our observations.

Furthermore, such correspondence holds well beyond our ability to imagine or visualize the physical world, as it happens in quantum mechanics or relativistic physics. As Michael Heller noted [19],

> *There are domains of reality, such as the quantum world, at the borders of which our language breaks down. This does not mean that within such domains anything goes — far from it. It turns out that mathematics constitutes a much more powerful language than our everyday means of communication.*

A dramatic example comes from recent developments in cosmology. Our understanding of the evolving universe has produced a theoretical model of the origin of the cosmic structures as being seeded by small density fluctuations in an otherwise highly homogeneous primordial plasma. These fluctuations are traced by the degree of anisotropy in the intensity of the cosmic microwave background. The amplitude of the fluctuations as a function of angular scale can be predicted on the basis of mathematical models that represent physical interactions occurring in the first 0.003 percent of cosmic age. Now, theory predicts a well defined degree of anisotropy as a function of the angular scale. The angular spectrum is expected to follow an acoustic pattern, with peaks and valleys, representing maxima and minima of density compression and velocity fields in the primordial universe. Recent observations have measured with high precision the statistical pattern at a variety of angular scales [26]. The agreement with predictions is wonderful. There are a few free parameters in the fit, which represent important information on the contents and dynamics of the universe: highly accurate observations thus allow us to measure those parameters. But the startling fact, in our context, is the dramatic evidence that our mathematical predictions meet the observed data at the boundary of the observable space-time, corresponding to a cosmic epoch of 14 billion years ago. Similarly striking results are routinely obtained in quantum physics experiments, in regimes completely divorced from our common experience.

Why so? What is it that makes our brains neural system capable of predicting how things behave in the most remote frontiers of the physical world? We do not know whether such faithful reading applies in an absolute sense. There is an ultimate limitation in the region of the universe that is accessible to us, and we will probably be left forever with an irreducible ignorance of what lies beyond [27]. We cannot exclude that the structure of reality beyond our cosmological horizon, or beyond some threshold at infinitesimal scales, will break down marriage with our mathematical language. Even so, what we already see today is more than sufficient to constitute a great mystery: what makes our mind so cosmically fit? The famous words of Einstein are today all the most fashionable: The most incomprehensible thing about the universe is that it's comprehensible. Perhaps even more passionate is the expression of Paul E. Wigner [28]:

> *The enormous usefulness of mathematics in the natural sciences is something bordering on the mysterious and there is no rational explanation for it. It is not at all natural that laws of nature exist, much less that man is able to discover them. The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift for which we neither understand nor deserve.*

The question "why is physics possible?" is not of the kind that physics itself can answer. Here science seems to touch a territory that extends beyond itself. As Joseph Ratzinger recently pointed out [29]:

> *Mathematics as such is a creation of our intelligence: the correspondence between its structures and the real structures of the universe [...] arouses our admiration and raises a great question. It implies, in fact, that the universe itself is structured in an intelligent manner, in such a way that there exists a profound correspondence between our subjective reason and reason as objectified in nature. So it becomes inevitable to ask if there must not exist a single originating intelligence, which would be the common source of both the one and the other.*

Every discovery is precisely an event of a new occurrence, made explicit, of this mysterious correspondence. Perhaps here is the source of the deep gratitude and joy that researchers experience when they reach new understanding, however small. Every new insight recalls the secret friendship of the universe with us, and satisfies for a moment our natural desire for connectedness with the universe [30], normally unconsciously lived. In letting itself be more understood, the physical world shows an attitude of openness to us, and we perceive ourselves as destined to a relationship with everything. It is as though for a fleeting instant the appearance of things allowed a glimpse of an ineffable familiar face at the roots of reality.

3.1.4 Sensitivity to ultimate questions.

As scientists move forward, they are continuously exposed to fundamental issues. Who are we in the immense cosmic picture? Is there a purpose in the universe? And what is the ultimate goal of our scientific knowledge? Is the order and richness we find in nature a signature of an underlying deeper Reality or is it just a bare fact requiring no explanation? Following Luigi Giussani, these questions reflect the *"religious sense"* of human beings [2], i.e., our constitutive relationship with the Infinite and our fundamental need of an ultimate meaning. Indeed, most great scientists have explicitly expressed a deep appreciation of ultimate questions about meaning, origin and destiny, with passages that sometimes have significant literary value (see Chapter 6 and Chapter 7 in [13]). For instance, as Einstein said [31],

> *The most beautiful and deepest experience a man can have is the sense of the mysterious. It is the underlying principle of religion as well as of all serious endeavour in art and in science. He who never had this experience seems to me, if not dead, then at least blind. The sense that behind anything that can be experienced there is a something that our mind cannot grasp and whose beauty and sublimity reaches us only indirectly and as feeble reflection, this is religiousness. In this sense I am religious. To me it suffices to wonder at these secrets and to attempt humbly to grasp with my mind a mere image of the lofty structure of all that there is.*

In many cases, however, these questions are only implicitly assumed. While these are rationally compelling, they clearly reach outside the domain of science. As Erwin Schrdinger recognized: Whence came I and whither go I? That is the great unfathomable question [. . .] for every one of us. Science has no answer to it [32]. Indeed, the most relevant issues of human existence regarding ultimate meaning, social life, personal existence, love and friendship are not addressed and resolved through the scientific method. Max Planck noted that Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are part of nature and therefore part of the mystery that we are trying to solve[33].

Science is not equipped to answer these questions, and they do not enter directly as an element internal to the technical discussion. Therefore, one can do physics without facing them directly. Indeed, scientists dont necessarily think of fundamental issues and some of them claim that questions of this sort are altogether irrelevant or meaningless. But this doesnt necessarily mean that scientists could do what they do without being in practice deeply moved by them.

The situation is perhaps similar to that of a musician composing a melody. He works hard, with passion, joy, discourage, or despair, depending on times. He tries a note after another, following his inspiration while carefully considering the rules of harmony. He is not thinking of what makes the particular combination of frequencies and timbres he just found to sound more expressive; nor is he necessarily pondering the nature of the yearning that his new melody evokes. He is totally absorbed in what appears to be purely technical work. In a sense, the longing that his music recalls has no place in what he does: it is not an element of the same nature as the piano, the staff, or the sound vibrations in the air. Yet clearly, our composer is constantly – though perhaps unconsciously – animated by a desire to express something, a profound reality he is moved by. Similarly, for an astronomer at work, the fundamental questions on the origin, destiny and meaning of the universe are not an object of his research in the same way as are the telescope and instrumentation he is using, or the quasars he is trying to observe; but those ultimate questions are continuously sustaining his deep motivation: they are not elsewhere with respect to his scientific work, rather, they act as silent and powerful engines moving his desire to know and understand.

3.2 Is certainty possible?

The classical falsification argument claims that the only possible outcome of a scientific observation or experiment is a negative truth. According to Karl Popper, no scientific hypothesis or theory can be considered true. Scientists do not deal with reality, but only with the models produced by their own minds. In his words [34],

> *Theories are our inventions, our ideas. They do not impose upon ourselves, they are our instruments of thought. We have developed them by ourselves. But some of these theories may sometimes bang into reality; and when they hit, we know that there is a reality, that there exists something that can tell us that our ideas may be wrong*

Reality, in this view, manifests itself in the process of scientific knowledge only in that it may contradict our ideas about it.

3.2.1 Converging signs

Indeed, Poppers description captures a genuine aspect of the way in which science proceeds, perhaps the most routine side of its course. However, our present insight into the physical world reveals that science has lead us well beyond the limits of a set of purely negative truths". It seems to me that today we know a number of facts about the universe that do not correspond to mere negations of hypothetical conjectures, but are instead solid conclusions on how nature actually works. Consider the statement: the Sun is a star. This is a positive truth, representing the conclusion of a long-lasting and winding scientific path. A long time ago, the claim the Sun is a star used to be a hypothesis, today no reasonable well informed person would have any doubt in accepting that statement as an incontrovertible matter of fact. The list of similar positive truths is exceedingly long: matter is made of atoms, a molecule of water is made by two atoms of hydrogen and one atom of oxygen; mammals have evolved after amphibians, the electron has both wave and particle properties; our universe is evolving... These facts are not self evident, but have now become as solid as the phenomena for which we have direct observation. Of course, this doesnt mean that we know everything about the Sun, electrons, water molecules or lifes evolution. We surely dont know everything about the universe (we still dont understand 95% of its matter-energy content!). Yet somehow we are sure of the validity of the above statements.

How does our reason move towards such positive conclusions? A single observation or experiment can only yield either a negative truth (à la Popper) or an indication — however, an indication is not an answer! But when we are in presence of a great number of concordant indications we may come to see conclusively what those clues mean. Normally, this is the way our reason is at work in the recognition of a positive truth: we see the point of convergence of several independent indications aiming in the same direction (See [35] and Chapter 5 in [13]).

To see an example, lets consider our belief that our universe is evolving. Cosmologists today state this very important conclusion with great confidence. However, they do not see directly a universe that evolves in time: what they do see is a wealth of indications of such evolution. A most immediate clue, under our eyes since prehistorical times, is the darkness of the night sky — but this alone would be a hardly convincing element [36]. Historically the first indication of an evolving universe came unexpectedly from the aftermath of Einsteins general relativity, when Russian physicist Alexander Friedmann showed that expanding or contracting world models emerged more naturally from the theory than static solutions [3, 37, 38, 39]. Then a series of crucial observations carried out in the 1910s and 1920s, culminating with the famous paper by Edwin Hubble in 1929, demonstrated empirically a linear relationship between galaxy distances (at that time limited to a few Mpc) and observed redshift, indicating an expanding space at large scales [40, 41]. Today this relationship, known as the Hubble law, is beautifully confirmed out to cosmological scales and the rate of expansion is measured with great precision [42]. Then in 1965 the dramatic discovery of the cosmic microwave background (CMB) [43, 44], independently predicted two decades earlier by George Gamow and his group [45, 46], provided a new powerful and direct evidence of a primordial hot cosmic phase. Not only the existence of the background radiation, but its detailed properties —blackbody spectrum [47], temperature anisotropy pattern [48, 49], and more recently the tiny polarized component [50]— measured by successive generations of experiments turned out to be fully consistent with signatures of an evolving universe back to its initial stages. Measurements of the CMB temperature as a function of redshift, exploiting the excitation of fine structure states of CI and CII [51, 52, 53, 54] give a direct confirmation that the universe was hotter when it was younger, as expected from expansion. Furthermore, progress in optical and infrared imaging and spectroscopy gave enormous evidence of an evolving trend in galaxies and active galactic nuclei. Recent data such as those on the Lyman-alpha forest on distant quasars, baryonic acoustic oscillations, gamma ray bursts represent new tesserae of the cosmic evolution mosaic. The number, strengths and independence of these clues is overwhelming: less than fifty years ago we were in the middle of a great debate between an evolving and a stationary cosmological picture; today we have a conclusive positive answer. Just as in biology, being sure of cosmic evolution does not mean to understand it all — nevertheless, evolution itself is a fact. Of course, it is quite possible that future development will change our outlook of the universe (or of biology), perhaps even modifying the language we use to describe it. But the multiple correlations indicating the evolutive nature of our universe (or of biological organisms) will have to be preserved and included in any forthcoming interpretation.

In general, in science we move forward through a long chain of signs or indications, hierarchically pointing to increasingly synthetic and relevant conclusions. The analogy with the way of reaching truth in other domains, e.g. in moral or theological issues, is remarkable [2]. What matters in a sound scientific context is that ultimately each elementary indication, at the bottom of the chain, is represented by a quantitative, controllable and repeatable measurement.

3.2.2 A wider reason.

This story gives a sense of why scientists can speak comfortably of invisible things like the expansion of the universe, or the electroweak force, or the evolution of life. They speak as if they had seen these things with their own eyes, but they never did. Of course they have to play responsible, but they are not crazy nor are they trying to cheat: they simply use their reason in a broader way than that we normally assign to scientific thinking. High confidence does not come cheap. Its not the outcome of a single measurement; rather it is the converging point of numerous independent and well established indications. A conclusion such as our universe is evolving does not result automatically from the data. No known algorithm or procedure can substitute human judgement, even in science [55]. This implies a working of our reason more similar to that of a detective than to that of a logician. It is only through a great amount of clear, diverse and repeatable observations, through the familiarity with a given phenomenon by generations of competent researchers, through continuous discussion within the scientific community over long periods of time that an initial hypothesis slowly can become transformed into a stable, positive conclusion. And then new hypotheses can be formulated as we can safely rely on a new solid starting point. Without the firm grounds of a positive certainty, our scientific creativity would probably suffer endemic self-doubt and insecurity, and would eventually vanish.

What kind of issues can become stable conclusions? As we noted, they are of qualitative nature. They describe first-order features of the physical world: existence, origin, evolution, structure, function, physical nature, composition, relationship with the universe. These are also the most significant and hoped-for final results of a scientific investigation. The great success of the experimental method rests on the identification of measurable quantities, on the mathematization of the relationships among them, on quantitative measurements, on rigorous logic. But below the surface of every quantitative step there lies the most interesting object: the hope to shed light on a quality of the phenomenon. When in a research program we take precision measurements (with error bars!) we normally hope to use them to discriminate between different conceptual possibilities: the interest of the measurement is not in the quantitative result per se, but in its ability to discern between different qualitative scenarios.

This explains the dynamics that moves large research projects. T The Large Hadron Collider (LHC) at CERN is the result of a colossal technological and scientific effort worldwide. In 2011-2012, the LHC has produced proton-antiproton collision of 3.5-4 TeV per beam, an energy never reached before. The scientific justification for such a monumental project was not —of course— to break a "quantitative" energy record, but to verify a "qualitative" prediction of the Standard Model: to verify the existence of the Higgs particle, responsible for the mass of all particles.

4. Conclusions

A commonplace understanding of the use of reason in science strongly emphasises the importance of inductive-deductive reasoning and demonstration ability. This would seem to require a highly specialized predisposition and talent, involving a remarkable but limited set of intellectual skills. However, we have pointed out that scientists in the practice of their work employ a much wider range of rational and personal capabilities than usually assumed. Indeed, in order to account for what we know about the universe through science, it is necessary to broaden our notion of what we normally mean by reason. Affective elements, not separable from our intellectual abilities, are essential for the onset and duration of any scientific enterprise. Sometimes it is granted that wonder and aesthetic sensitivity are involved in the beginning of scientific research, but they are normally thought to become irrelevant at the end of the process: as the real knowledge attained by science advances, the initial fascination is believed to dissolve and vanish. We have suggested that, on the contrary, an aesthetic component is constitutive in the process of science. This is reflected in the fact that an attitude of wonder turns out not only to persist, but even to be enhanced, by a new scientific discovery. Scientists are solicited to consider ultimate questions by their continuous exposure to the orderliness, beauty and intelligibility of nature. While answering them is clearly outside the domain of science, sensitivity to the ultimate questions seems to act as a fundamental – though often implicit – motivation of scientific interest, creativity and dedication. Conceiving an observation or experiment involves rational processes that are analogous to the ability to frame and ask questions. Finally, while classical falsification seems to limit the result from any single experiment to a negative truth, the quest for a positive truth is approachable as a convergence of a large number of independent clues.

All this implies that scientific investigation calls into play a wider variety of intellectual and personal features than usually thought. If this is the case we may ask, what intellectual virtues, in addition to the logical-deductive dimension typical of the scientific approach, would we expect to be important in a fertile scientific mind? First of all, it seems necessary a disposition to be surprised, moved, affected by the physical reality. This perhaps has to do with the trait of simplicity that is naturally found in children, and which is often recognizable in the personality of great scientists. It is similar to the simplicity of the poor in spirit, who is more attached to the truth of the object than to his own idea about the object. This is the key for a sound approach to a scientific observation or experiment, which favour those who are free from preconceptions, easy to give up their ideas when new evidence comes in. The intellectual attitude of simplicity might also be related to the ability to ask simple, sharp, decisive questions — just as only kids can do. A second vital attitude for a scientific mind is humility, as it establishes the correct relation of the person in front of the mystery of the universe. Humility here has nothing to do with self-dismissal, of underestimation of our skills, but it is rooted in the rational awareness that we are not the makers of reality. No scientific description of the world that we may develop will make us the owners of the universe. In fact, as our knowledge advances our sense of ignorance will also increase: the volume of the sphere of our understanding of the universe grows and so does the surface of contact with the unknown.

Simplicity, humility: far from being sentimentalistic reductions of reason, these attitudes appear as pillars of a truly rational mind. Interestingly, these are the same intellectual virtues that we need to recognize the infinite Mystery that lies beyond the appearance of things, as described in chapter five of Matthew's Gospel, of whom the entire universe is a magnificent metaphor. In the words by Goethe, famously quoted [56] by Max Planck,

> *The greatest joy of a thinking man is,*
> *having explored the explorable,*
> *just to admire the unexplorable.*

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