A guided tour of infinity

The question of infinity started its journey in our minds as soon as the first rational human beings looked at the sky with inquiring eyes. The subsequent history of mankind brought along several other flavors of infinity: infinitely small, infinitely complex, infinitely fast, infinitely precise… But the real issue is, after all, what infinite stands for, what it represents in our understanding of Nature and of the human mind. How do we define it? What are the consequences in our daily lives?

Of these two questions the former has probably the simplest answer: there is no way to define infinity in concise terms. In fact infinity is not defined by what it *is*, but by what it *is not*. Only metaphorically can infinity be assessed and in that sense it is one of the rare concessions that science does to poetry. It is where the scientist's mind can roam free and where (almost) everything is possible. It is the place where the artist and the scientist can travel side by side without being hampered by the strict constraints of reality.

As usual, freedom is not without its perils and this case is no exception. Although infinity is, by definition, always out of reach, science has taught us that what we assume to happen there can have profound consequences for what we expect to observe around us. For this reason scientists use infinity as a basic tool to constrain theories to reality. It should be added, incidentally, that they also use it to send to oblivion objects and concepts which are not relevant (or convenient) for the discussion of the phenomena under scrutiny, which makes infinity a very handy, fuzzy concept provided it does not strike back in the scientist's own backyard. Modern Physics -- notably Quantum Field Theory-- uses this technique more often than caution should advise, but at present no other choice is left open to us by a theory which is functional, but incompletely understood.

Until the twentieth century our Universe was unbounded both in space and in time and infinity permeated our knowledge of Nature without restraint. Infinity was a useful concept, handy for calculations and for neglecting parts of our world, but no more than that. Most of this has changed in the last hundred years for we have discovered that in many ways what we considered infinite was only so due to an illusion resulting from our limited knowledge of Nature. One of the most profound consequences of Modern Physics is that it has shown how, in some aspects, our Universe is bounded.

This limitation process started in the late nineteenth century in several directions at the same time. The strange properties of light induced Michelson and Morley in 1881 to measure with high precision the speed of light. It was not the first time that this was attempted, since Galileo himself had already tried to measure it without success. Descartes, after him, defended that it was infinite. In the late seventeenth century Ole Römer, based on the peculiar anomalies in the sequence of eclipses of Io, one of Jupiter's satellites, showed that these anomalies were due to the finite nature of the speed of light. And, finally, from this result Christian Huygens computed for the first time this unimaginably large speed. But what Michelson and Morley were interested in was not the speed of light *per se*; they wanted to know how it related to the speed of the observer. The outcome of their experiment opened the first breach in the otherwise seemingly impenetrable wall of Classical Physics. It marked the beginning of a bounded vision of Nature.

Their experimental result, complemented in 1905 by Albert Einstein's insight, showed that there is no such thing as infinitely fast. Nature is, in this respect, limited to speeds smaller than the speed of light in vacuum and therefore not everyone is allowed to communicate in our Universe. Only those who can, at most, exchange a light signal between them can exchange information. Being a limiting velocity, the speed of light in vacuum is thus the same for everyone, a fact that baffles anyone facing it for the first time. It violates the cherished law of addition of velocities which accompanied mankind since the times of Galileo. In the process it also twisted the concepts of space and time to such an extent that our previous vision of the Universe became totally unrecognizable.

This was not the only direction in which a hard boundary was found. Within Classical Thermodynamics the concept of absolute temperature scale emerged from the study of gases and, in particular, of rarefied gases. Absolute zero, equal to -273.15 degrees Celsius, made its way in Physics through a temperature scale which was bounded only from below. However Walther Nernst, in the first years of the twentieth century, showed that this lower limit was not attainable: it is impossible to reach the absolute zero by means of a finite number of operations, a fact which is presently known as the Third Law of Thermodynamics. What Nernst showed was later completed by Quantum Mechanics with the concept of *zero point energy*. But what is important is the fact that absolute zero can only be attained through an infinite number of steps. The boundary exists, but the road to it has no end.

The limitation process continues to the present day pushing the realm of infinity to new areas. In a way, this was to be expected: as Nature is better understood in all its aspects we start to discover the rationale (that is, the boundaries) that allow it to function harmoniously in its most intricate details.

We also know by now that there is no such thing as infinitely precise. Traditionally we were expected to always be able to specify with the highest precision both where we are and where we are heading to. Quantum Mechanics tells us every day that this is no longer true at the subatomic scale. Nature is thus, in this sense, inherently imprecise, a fact that allows it, actually, to explore possibilities in a much more efficient way. What became precise at this scale are no longer positions and velocities but the *probability* for a system to be in a given state. The evolution of this probability can be predicted in a totally precise and predictable way through the Schrödinger equation. The infinitely precise acquired thus a completely different meaning and scope.

Time, the eternal home of infinity, became also somewhat limited in the last hundred years. We realized that the present Universe had a beginning and thus its life did not extend indefinitely in the past. We still do not know how far its life will extend in the future, but there is a non-zero probability that it will not extend into the infinite future.

Also, the precision with which we are able to measure time became limited. Quantum Mechanics has shown – in parallel with what happened to position and velocity— that energy and time are connected in such way that only one of them can be precisely measured at the atomic and subatomic scales.

We are at present facing the infinitely complex in Life Sciences, Mathematics, Economics and essentially all branches of Physics and Chemistry. Statistics provides us with a way to tame part of the difficulties, but it gives, at best, a global scale overview of the problems. Computers can help somewhat to mitigate our limitations, but still on an insufficient scale for most problems. So, in this frontier we can consider that infinity is still pretty much out of grasp and that it will stay so for the near future.

One hundred years ago it was the “ultraviolet catastrophe” induced by the description of blackbody radiation that signaled the need for a fundamental change in the way we perceived the interaction of radiation with matter. It was the infinite predicted by the Rayleigh–Jeans Law describing classically the spectrum of blackbody radiation that triggered Max Planck in 1900 to introduce the concept of energy quanta. Since then infinity has been the hallmark of all scientific revolutions. Through it we can trace, in the last hundred years, the evolution of our knowledge of Nature both in the microscopic and macroscopic scales.

The need to harmonize Quantum Mechanics and Special Relativity has lead Paul Dirac in 1928 to propose the concept of matter and anti-matter. Since the experimental confirmation of this dual aspect of Nature by Carl D. Anderson in 1932, physicists take out of the vacuum all sorts of particles and antiparticles. Void became the busiest concept known to mankind, a fact which constitutes for sure the most ludicrous revenge of Nature: to make of the supposedly emptiest place a bottomless reservoir of fundamental constituents! The situation is so dramatic that the Physics of the last fifty years can be accurately described as the ultimate study of the vacuum properties.

One the most surprising aspects of modern Physics is the sense of unity that permeates from the infinitely large to the infinitely small. Not only we pushed the boundaries of our Universe very far in both directions, but we also realized that they are irremediably intertwined. Time scales also became strongly interdependent since processes occurring on very short time intervals condition in many ways the fate of the Universe at the infinitely large cosmic time scale. In other words, the way elementary particles interact dictates how the Universe evolves in the cosmic time scale. Reciprocally, since we know by now that the speed of light in vacuum is finite and unsurpassable, what we see at the borders of infinity of space gives us information about processes that occurred close to the beginning of time.

The vision of a fully interleaved infinitely small and infinitely large is presently such a cornerstone of Modern Science that CERN and ESA decided to bring it to the general public's attention through the initiative *Origins 2013 - a European Researchers' Night event* which took place in September 2013 in Bologna, Paris and Geneva.

But maybe the most spectacular exhibition of this unity of scales is the measurement of the Cosmic Microwave Background (CMB) radiation spectrum initiated by NASA's COBE satellite in 1990 followed, with a much higher precision, by ESA's Planck satellite between 2009 and 2012. This thermal radiation is a permanent footprint left by the evolution of our Universe when it became transparent to light as it is today. The incredible accuracy with which the curve found by Max Planck in 1900 describes the CMB radiation spectrum is nowadays one of the most striking demonstrations of a primordial Big Bang and of the Standard Cosmological Model. To observe --with an amazing precision -- in the large scale of the Universe the same curve which announced the existence of quanta in the subatomic world is a landmark in the revolutionary vision opened by modern Physics and modern Cosmology.

We know since long that only four interactions – gravitational, electromagnetic, strong, and weak forces – are responsible for all processes at work in the Universe. It was the presence of infinity at energy scales of the order of 1 TeV (10^{12} electron volt) in the original Fermi model for the description of the Weak Force that led to the discovery of gauge theories and ultimately to the introduction of the Higgs field. These two coalesced in the present day Standard Model for the Strong and Electroweak interactions. Infinity was maybe the herald of the unification of all fundamental forces.

Accelerators such as the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) take us even closer to the beginning of time by studying processes that occur on the minute scale of a tiny fraction of the proton size. The results of the LHC experiments, above all the discovery of the Higgs particle, have shed light on the structure of the Natures' microscopic realm. This new particle is the key to understand the origin of mass and therefore the key to understand the conditions that prevailed close to the birth of our Universe and its fate in the infinite future. Only time will show how far reaching this discovery is and what lays beyond it.

It was also infinity at different energy scales that lead scientists to consider the existence of a fundamental symmetry in Nature relating fermions (particles possessing half integer spin) and bosons (particles with integer spin). Whether this *Supersymmetry* (or, in short, SUSY) is present in Nature remains to be seen, but the problem which gave rise to this proposal is still there. Infinity is illuminating the unknown whether we are able to find the way towards it or not.

The LHC program is actively pursuing the search for SUSY. In general it is searching for any hint of objects which might exist beyond the ones known so far and which are described by the Standard Model. These new objects must necessarily be there since their absence has the immediate consequence that the fundamental parameters of our Universe would have to be tuned to an impossible precision of 1 part in 10^{30}. These numbers are akin, for all practical purposes, to infinity and thus point to a fundamental missing piece in the puzzle of our Universe.

To make our position even more fragile, we discovered in the outskirts of the Universe that mass had reserved for us yet another surprise. We knew since some time that mass was concealed in the form of a so called “dark matter”, but we discovered almost fifteen years ago that an even greater amount is hiding in the form of “dark energy”. Invisible mass seems to be the stuff our Universe is made of to a very large extent. The fate of the Universe in the far future lays therefore even more on the edge of our observational skills, that is, on the frontiers of infinity which must be pushed even farther, be it on the infinitely small or infinitely large, to unravel what further surprises evolution reserves us.

The twenty first century is beginning with a panorama very similar to the one mankind was facing one hundred years ago. Data is accumulating about things we have no clue what they mean, how they are related to each other, and in which way they connect to what we presently know and understand. Paraphrasing Lord Kelvin’s famous words, we see the clouds gathering in the horizon, but we still have no idea which tempest they bring with them. One hundred years ago Lord Kelvin’s clouds were announcing Quantum Theory and Einstein’s Relativity which changed irreversibly the way we perceive the Universe. What the present clouds announce is not yet clear, but they have the potential to revolutionize once more our vision of Nature.

At this point it is finally possible to discuss the second question we posed at the beginning of this text, namely the importance of infinity in our everyday lives.

Why indeed should we worry about infinity if it cannot be attained in any circumstance? Why should we be so concerned about such an elusive goal?

If the reader takes a moment to muse over these two questions the answer will impose itself: infinity is in fact the one and only motivation for discovery. By definition, infinity always lays beyond what we know and for this reason it is in the direction of infinity that we have to search for the unknown. It is the infinite that pushes mankind to constantly perfect its thought and observational tools moving the frontiers of knowledge farther and farther away. Indeed, each time we change the outposts of infinity we gain further insight over the fundamental processes of Nature.

On the trail to infinity humankind leaves permanent traces. A simple prehistoric stone tool as well as a spacesuit are beacons signaling where we passed. Some of these traces are very humble, some are very important, but all are necessary. On this trail some of the steps were easily overcome the first time, some had to be experimentally rehearsed over and over again until it became clear how to safely move forward. All traces are there to show where we came from, the difficulties we faced and how we must proceed.

Edgar Martins' photographs bear witness to the landmarks we leave on the road to the infinite. Standing there, eternally immobile, belonging to humankind but left behind as it advances to new whereabouts, these signs represent our continuous struggle to understand Nature. Always in the present, yet always in the past -- for each photograph depicts, by its own nature, a reality which is already in the past – these signs delineate the path of discovery. They are the footprints of Science.

Each one of the portrayed objects, built to explore the outskirts of our knowledge, contains in itself the sum total of what humankind learned until the moment the object was constructed. In a simple glove is condensed the knowledge of the intimate structure of matter, of the four basic interactions at work in Nature and of the local structure of the Universe. However, this simple glove, or spacesuit or indeed any of the objects portrayed in these photographs extend beyond all this. By design or by chance the main purpose of these artifacts is to lead us towards the unknown. The humans wearing them perform definite steps to clear a few more inches out of the path of knowledge and lead us further in the quest for infinity.

This quest continues relentlessly every day. Soon the Large Hadron Collider at CERN will create the highest energy densities ever produced by man in the hope of unravelling new secrets of Nature's microscopic structure. They will bring us even closer to the beginning of time. Space missions by ESA and NASA will continue the program of the COBE and Planck spacecrafts and hunt for tiny anisotropies in the Cosmic Microwave Background, pursuing the secrets of the Universe's birth. For sure new insights will come from unexpected research directions. Together all these efforts will coalesce into a different vision of where we came from and where we are heading to. New boundaries will be found and new infinities will appear. New landmarks will be built and left behind. New landmarks necessarily depicting a completely different vision of the infinite but to which we must look in the quest for new paths of discovery.

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