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Big science and small science: reflections on the relationship between science and society from the perspective of physics

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> The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science. (Albert Einstein, *The World as I See It*)
>
> Chester V: 'There's no such thing as small science, only small scientists.' (*Cloudy with a Chance of Meatballs* 2)

In this chapter I will discuss some of the possible answers as to why science is a valuable enterprise. If this is accepted, then scientists should enjoy a substantial degree of freedom from various forms of restrictions. Financial restrictions obviously call into question wider issues about the morality of resource rationing. Other forms of restrictions, based on ignorance, fear or political or ideological credo, are harder to justify. Scientific freedom is not just a political or ideological matter. It is also a matter for scientists to actively deal with: it is the role of scientists to explain, in accessible terms, the importance of scientific endeavours that may appear either grand and remote, incomprehensible and detached from the life of many laypeople, or otherwise frivolous and trivial. I will try to take on this role, and discuss examples of seemingly grand and frivolous science, explain their purposes and importance and show that there is a big added value to society from small and big science if they work together.

Big science and small science: two examples

It is not uncommon, during public talks or among friends, that an astrophysicist like me is asked: 'What is the purpose of scientific research?' Or even more specific or challenging questions, such as: 'What do astrophysics (or astrophysicists) do for us?' Other questions, somewhat related, are 'Why spend billions on a particle accelerator or a satellite pointed towards deep space while our problems are exactly at 180 degrees?'

Whatever perspective we adopt, science can be defined as an endeavour aimed at expanding the horizon of the human race in space and time:

expanding into deep space and increasing our life expectancy. This process of expansion requires two parallel avenues: scientific research through big and small science. Big and small, as applied to science, refer mainly to the amount of resources – for example funding – dedicated. One example of big science is the Large Hadron Collider (LHC) in Switzerland, with building costs roughly estimated to about €4.5 billion.

The LHC is the world's largest and most powerful particle accelerator. It is built as a large underground ring (100 m deep in the ground) 27 km long in the vicinity of Geneva in between France and Switzerland. It is by far the most complex machine ever built and also the largest in size. It was built by the Conseil Européen pour la Recherche Nucléaire (CERN) between 1998 and 2008 in collaboration with over 10,000 scientists and engineers from over 100 countries, as well as hundreds of universities and laboratories all over the world. It is truly an enterprise that required the skill and abilities of people from the entire world. The LHC generates two beams of elementary particles rotating in opposite direction inside the accelerator. When the beams collide, the collisions happen at extremely high energy to test fundamental physics, that is, our current understanding of the micro world. There are many open questions in physics that the LHC will address: what is the nature of time and space? What are the laws governing the forces between elementary particles? Are there any other spatial dimensions in addition to the three dimensions we are familiar with? Where is all the matter in the universe coming from? And many more.

These big science projects, with large associated budgets, have emerged only relatively recently – perhaps in the last three or four decades – probably triggered by the development of the atomic bomb (the Manhattan Project). Beside the LHC, another big science project would be a space mission. A European space mission costs around €2 billion which is equivalent to the cost of six Airbus A380s. These enterprises are funded by consortia of many countries simply because a single country – at least in Europe – would not have enough dedicated resources by itself.

Science does not progress exclusively through big projects such as the LHC or space projects, however. There are many examples of small science. The discovery of graphene might be a good example. It cost a few euros for Sellotape and a few pencils. Another example is the so-called 'Markov's chain' which originated from a seemingly trivial argument between two scientists, and which had an unimaginable impact on the day-to-day life of many of us today. I will go back to the Markov's chain later in the chapter. Before that, I would like to reflect on the importance of the LHC, as just one example of big science. Similar considerations can apply to different types of big scientific enterprises.

How big science expands human horizons in space and time

One recent achievement of the LHC is the detection of the Higgs boson. The Higgs boson is a new fundamental particle with a very special role: it generates the masses of all other massive particles. This mechanism of generating masses was predicted but not verified experimentally. The Higgs particle is one of the fundamental blocks of nature. We can say that through the LHC we have expanded our knowledge of basic fundamental physics.

These are the 'scientific' facts: that is the way in which the LHC has 'expanded human horizons'. But there is another less obvious, but no less important, way in which the LHC, and all big science, can expand horizons: a different kind of horizon. Big science improves collaborations among states, overcomes ideological boundaries and cultural differences. The political impact of science in preventing or solving existing political conflicts ought not to be underestimated.

The LHC employs more than 10,000 scientists of the more diverse nationalities – including for example Palestinians and Israeli. This is arguably an example of the 'sharing' process of moral values that might help solve some of the clashes among various cultures and populations. If we build stuff together it is much more difficult for us one day to destroy it. Science – not only big science – fulfils a quest for knowledge which, in turn, generates a better world, but it has the potential to generate a better world in moral terms as well. A better world is one in which moral values are shared among the largest possible population. It is a world where children are accustomed to grow together with the allegedly 'different', because difference is added value. Large international collaborations, in fact, typical of big science projects, exploit the averaging effect and might be able to produce a new generation of scientists, which in turn might contribute to a new generation of politicians. Science not only improves generically the human condition in its physical dimension, for example by providing better technologies that stretch life expectancy and improve quality of life. Science generates a big added value in making people better by favouring collaborative efforts among scientists from different nations/backgrounds/religions/skin colours/sexual orientations etc. But it does not stop here: as Corbellini and Sirgiovanni (Chapter 13 in this volume) also note, science requires abstract thinking through expressing hypotheses and developing the ability to rationally evaluate them, and this in turn improves people's capacity to imagine situations, and thus to identify with other people, other animals or future generations. Training in abstract thinking, and thus scientific education, makes us all better at seeing beyond our moral, geographic, personal or cultural reference systems.

Small science: an example

Andrey Andreyevich Markov was a Russian mathematician who made important contributions to various fields of mathematics towards the end of the nineteenth century. In particular, he founded a new branch of probability theory by applying mathematics to poetry. What is even more remarkable is that he applied mathematics to poetry to prove a point: his opposition to a fellow Russian mathematician, Pavel Nekrasov. Markov referred to Nekrasov's work as 'an abuse of mathematics' (Ondar 1981). The argument between the two mathematicians revolved around the law of large numbers. The law can be described with a simple example: if you keep flipping an unbiased coin, the proportion of heads will approach 1/2 as the number of flips goes to infinity. This notion seems intuitively obvious, but it gets slippery when you try to state it precisely and supply a rigorous proof (Hayes 2013). There was a basic and important philosophical difference between the two mathematicians. Nekrasov was at Moscow University, a stronghold of the Orthodox Church, where he started his studies in theology and then mathematics. Markov was a sort of rebel against all authorities. When the Russian Church, for example, excommunicated Leo Tolstoj, Markov asked to be excommunicated too. It goes without saying that the request was immediately granted.

In 1902 Nekrasov published a paper in which he discussed how he used the law of large numbers to settle the centuries-old theological debate about free will versus predestination. He claimed that voluntary acts – expressions of free will – are to be considered as independent events in probability theory. He also required that the law of large numbers applies only to statistically independent events. Therefore, he claimed, people act out of free will (in line with the philosophy endorsed by the Catholic/Orthodox Church). In fact, according to the *Catechism of the Catholic Church*:

> God created man a rational being, conferring on him the dignity of a person who can initiate and control his own actions. God willed that man should be 'left in the hand of his own counsel', so that he might of his own accord seek his Creator and freely attain his full and blessed perfection by cleaving to him. (2012)

Markov could not resist trying to invalidate his opponent's claims. Although Markov certainly disliked Nekrasov's background, he used a purely mathematical argument to contrast Nekrasov's hypothesis. Markov pointed out a mistake: Nekrasov assumed that the law of large numbers applies only to independent events. Although it looked like a reasonable assumption, Markov went on to show that the assumption was not necessary. To make his point he analysed the text of Alexander Pushkin's novel *Eugene Onegin*. He wanted to study the statistics of vowels and consonants in poetry to evaluate their correlations, for example the probability that a vowel will follow another vowel or a consonant, and so on. He successfully extended the law of large numbers to correlated events. He created what today we refer to as the 'Markov's chain' which is not a solid object but rather a mathematical tool. A Markov's chain is a way to model reality. A very simple example could be an attempt at modelling the weather. Suppose we want to model the 'chance' of rain of tomorrow based on our knowledge of today's weather. From past experience we know that if today is sunny (no rain) then tomorrow most probably will be sunny too. If on the other hand today is rainy there is a good probability that tomorrow will be rainy too. Markov's chain is a mathematical tool to predict the weather tomorrow given knowledge of today's weather and the associated probability. For example, we can say that eight out of ten times, if today is sunny, tomorrow will be sunny too and, eight out of ten times if today is rainy, tomorrow will be rainy too. So, to make a 'chain' we just feed tomorrow's result back into today. Then we can get a long chain like this:

> Rain–rain–rain–no rain–no rain–no rain–rain–rain–rain–no rain–no rain–no rain . . .

A pattern will emerge: there will be long 'chains' of rain or no rain based on how we set up our 'chances' or probabilities.

All of this mathematical machinery could have been simply recorded in some Russian mathematical journal with absolutely no practical use. However, it turns out that Markov's chains find use in many modern applications. To cite just a few: identifying genes in DNA molecules, algorithms in voice recognition and last but not least the Google search engine – a business worth more than $60 billion.

Small or big science, then?

In the opening section of this chapter the concepts of 'big' and 'small' science were introduced, with a few examples of each. Although the distinction between big and small science is widely accepted mostly in terms of quantity of funding, human resources invested, etc., in another sense all science is equally science. Both big and small science is equal in its pursuit of knowledge and both aim at expanding human horizons.

Even the distinction between science and the arts is not clear-cut but is subject to some degree of arbitrariness. Galileo's reflections on scientific method, a remarkable example of philosophical investigation, allowed the flourishing of empirical sciences and paved the way for the emergence of different scientific disciplines. This, as Lachmann and Corbellini point out in this volume (Chapters 1 and 13, respectively), has had wide-ranging and profoundly positive effects on both the quality of human life and the extension of life expectancy. However, in this progress of specialisation it sometimes appears that awareness of the common roots between arts and science has been lost. It is remarkable that in ancient Greece, what we today call *art* was called *techne* (techniques, or mechanical arts, which also included what we would call arts – music, for example), and it was the gods' prerogative, which they donated to humans to overcome their intrinsic fragility. Markov's chain is certainly one of the many reminders of these common roots which also exemplify humanity's curiosity and striving for knowledge. Markov's chains serve to establish a sort of equivalence between hard science (mostly mathematics and physics) and arts such as poetry, music, painting etc. The pleasure that many humans experience through various forms of arts and science (through music, figurative arts, narrative, as well as by resolving mathematical hurdles and other dilemmas, both in science and philosophy) must have some evolutionary advantage: the capacity to see patterns has allowed humans to evolve up to a point where we now exercise significant control over our physical environment – in good and bad ways.

So, small science is equally as valuable as big science. Not only do they both represent equally valuable pursuits of knowledge, but small science often serves as a seed to big science. Many major big discoveries have been made as a result of small science. Many small scientific projects explore a large number of different ideas. Those relatively few projects that are successful are then used as seed for big projects. Small projects are risky, so they might turn out in failure, but those few that are successful have a big return in terms of investment.

Conclusion

Science is an enterprise aimed at understanding the world around us and at improving living conditions, for humans, for other animals and also for the planet as a whole. But as I suggested at the beginning of this chapter, science does something else: it can and does considerably enlarge human horizons in time and space. Human horizons in time, as individuals, has certainly been enlarged, as human life expectancy is now approaching 100 years (see Giordano Chapter 2 in this volume). The opening of the space frontiers is enlarging our spatial horizon. Technically we are already capable of sending people to Mars, and with larger investments it would not be too difficult to approach stars closer to Earth (a few light years away). This is important, because should we trigger the irreversible decay of the planet Earth – or more precisely perhaps, should humans make conditions on planet Earth inimical to human life itself (think of climate change, for example, or overpopulation) – the continuation of the human race may rely on our ability and willingness to move to other planets. This, obviously, can only be achieved through solid support to basic and applied science. Scientific freedom, thus, is without exaggeration essential to the continuation of human life, and no longer solely essential to the amelioration of living conditions.

Of course, scientific endeavours must be regulated: particularly for big projects, the larger the amount of funding needed, the more scrutiny and peer review is given. But even small projects, and even theoretical research, are subject, at the very least, to peer review. However, even within the inevitable boundaries of accountability and resource rationing, scientists should enjoy significant freedom of enquiry and research. Restrictions based on fear or political or ideological creeds, are, as I noted in the introduction, hard to justify. Of course, particularly in the course of the twentieth century, science has been associated with a number of atrocities (Nazi experiments are not alone – many other atrocities have been committed both in Europe and in the US in the name of science). Cases of scientific fraud have been uncovered and distributed to the public via the media, in which pseudo-scientists have published results that were falsified, or made claims that proved unfounded. The crimes and misdemeanours of the few should not discredit science per se, but it is notoriously difficult for a profession to regain trust when that trust has been eroded. Scientists can play an important role in attempting to elevate the reputation of science. Through public engagement, for example, scientists could and should explain in accessible terms the importance of their endeavours, the importance of scientific projects and discoveries that may appear either grand and remote, or otherwise frivolous and trivial, and explain the nature and purpose of their specific area of expertise, which may appear detached and difficult to understand to non-specialist members of the public. As Corbellini also notes, this is not just a task for scientists or science correspondents in newspapers, magazines and the media more broadly: scientific education is the responsibility of every state. Through the long journey of compulsory education, education in science and scientific methods is crucial to the enhancement of people's ability to engage objectively with science, to free themselves from the spectre of the atrocities committed in the name of science, of frauds committed in the name of fame or of money, and to evaluate more rationally the methods and aims of various scientific enterprises. Of course, we all need to accept that perhaps many scientific projects will not bring any major or immediate enhancement in our day-to-day life. But perhaps one in a thousand or more will open a new direction. As in the case of Markov's chain, somebody may then find a practical use for discoveries that may appear trivial today, and maybe create the next 'Google'.

References

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