Evolution of science II: insights into working of nature

Mayank N. Vahia

We attempt to provide a comprehensive model for evolution of science across millennia, taking into account the contribution of intellectual traditions, cultural value systems and increasing sophistication of humans in their study of nature. We also briefly discuss the role of technology and its interplay in the evolution of science. We identify five primary approaches to the study of nature, namely, ad hoc formulations, religious approach, pragmatic approach, axiomatic approach and the logic-based approach. Each of these approaches has had its prime periods and has contributed significantly to human understanding of nature and has also overlapped within a society, playing a central role over human evolution at some stage. We surmise that the currently dominant axiomatic method will reach its limit due to its complexity and may never be fully formalized. We suggest that future progress of science will be more logic-based, where we will use experimentation and simulations, rather than axiomatic firmness, to test our understanding of nature.

Keywords: Evolution of science, science and society, understanding science.

Human studies of nature

WE had analysed[1] the evolution of human intelligence and perspectives on nature that ever since humans – even archaic humans – obtained intelligence beyond their survival needs, they began to study nature to improve their living conditions. There is significant evidence for development of technologies by archaic humans and of careful burial of the dead by Neanderthals, suggesting certain views and respect for the dead. Here we discuss the evolution of the thought process resulting in our present perspective.

Early humans would not have been able to comprehend the variety in nature. Even modern humans cannot make such claim. However, he/she must have been able to see that there were rhythms and consistency in the working of nature, but these patterns were not exact. Given the nourishing nature of land and the need for rains, our first instincts seem to have been to relate Earth to Mother and Sky to Father. But Mother Earth and Father Sky also provide imperfect/inconsistent patterns and the causes of these deviations were difficult to fathom. It is at this stage that the idea of God would have arisen. Mother Earth figurines are amongst the earliest known artwork[2]. Many early cultures show rock art with a human form holding Sun and Moon in two hands.

Mayank N. Vahia is in the Tata Institute of Fundamental Research, Mumbai 400 005, India.
e-mail: vahia@tifr.res.in

Role of technology in the evolution of science

Technology and science have been feeding each other for their mutual benefit. In manipulation of nature by early human, technology probably preceded analytical studies. The growth of human technological capabilities is discussed elsewhere[1]. It shows the relation between technologies of scientific discoveries. A typical scientific discovery gets gradually converted to technology, which opens up various possibilities leading to the next set of useful technologies. Civilizations progress by effective technology that science provides and not by novel scientific insights alone. The earliest technological evolution, from early stone tools to construction of dwellings, was developed from an instinctive understanding of nature. Even these, especially the skills needed to create flaked tools, animal traps, controlled fire, etc. required a certain basic understanding and acceptance of the objective nature of the environment. Scientists take great pride in the impersonal nature of their work but cultural influences play a significant role[3]. While technology plays a crucial role in the evolution of a society (figure 4 of ref. 1), it also provides new insights into the working of nature. For example, the realization of the power of steam to do work eventually led to the field of thermodynamics. There are several such examples in science. In the present study, we do not discuss this subtle interaction between the two and integrate both, technological and scientific advancement in a single unit.

There is no denying the elegance in the way nature works. To begin with, repeatability of a property of physical universe, conservation of matter; and other evidences of natural consistency would have given them faith to study nature even further. A section of human intellect was therefore always directed towards identifying patterns and keeping count. While counting can start with commerce and then grow into complex ideas, geometry is essentially a gift of astronomy. This systematic study of quantifying the mechanisms of nature would have had a profound effect on humans. Different cultures have approached the study in different ways[4–6], viz. *ad hoc* approach; religious approach; pragmatic approach; axiomatic approach and the logic-based approach.

We discuss in detail each of them in the following subsections. In Table 1, we give a summary of the different methods. While we have classified these methods for convenience, many of these approaches have overlapped in different cultures and the path is not monotonic. For convenience and in keeping with a more broader approach, we have ignored culture-specific variations and evolutionary paths. To illustrate the differences, in Table 1, we give an example of how each culture would treat the observations of fire on a hill. With each approach we illustrate the characteristics of the culture with examples from astronomy. The relevant astronomical techniques imply a whole host of other technological developments; but, for brevity, we do not discuss them.

Ad hoc approach

This purely utilitarian approach is entirely driven by survival needs and instinctive understanding of the properties of materials employed to improve survival. No systems are formally studied and little formal planning is included. Systems are built based on intuitive feel and experience of materials and their combination to create the necessary tools. All science begins this way. While this may be called primitive, a significant amount of informal understanding of materials is required to be efficient. During this period, one typically finds the advent of rock art with astronomical theme and megalithic structures designed to keep track of the movement of the Sun. The method is still prevalent in many low technology activities.

Religious approach

This approach assumes that nature and the universe is driven by a supernatural power, which tracks everything and controls all events, and evolution of any event is based on the whims of the supernatural being[7]. The wishes of this supernatural being are dependent on the nature of human behaviour, and have serious problems on issues such as free will and the manipulation of living by the superhuman. As such, it discourages any analytical study of nature and encourages expenditure of time and resources to ensure that the superhuman remains positively disposed towards humans. It therefore aggressively denies and discourages formal studies of the working of nature. It can also give rise to irrational belief systems and occasionally hide analytical studies of nature within its reach by giving it a different perspective. It has also moulded and changed the manner of growth of civilizations. The extent to which dominance of scientific method can be negated by religion can be seen today in many West Asian countries, which began their history by encouraging scientific thoughts but find their scientific approach completely stifled by the rise of religious dominance severely restricting its future prospects[8].

During this period, the most prominent feature is the evolution of megaliths in the sites of important religious or semi-religious festivities, chiselled rock art, as well as rise of myths connecting heroes, gods and heavens. Elaborate stories of times when gods ruled the earth and interacted with humans are created and rituals are designed to keep the gods happy.

However, the interplay between religion and science has often been complex since religion also evolves with time[9] and many scientists would pay their respects to the elegance of science. The rationalist approach to life and universe is often not easy to escape and atheism is often not easily accepted, largely driven by the manner in which human intelligence has evolved[10]. Many scientists such as Isaac Newton were involved in religious studies or have been practising formal religion. The relation between science and religion and the manner in which mutually differing emphases on the core entities that govern the world have been handled by human civilizations were also discussed earlier[11].

Pragmatic approach

This approach assumes that nature works with mathematical precision, but its exact reason is beyond complete comprehension. It implicitly assumes the reason nature behaves the way it does is beyond comprehension. With increasing levels of understanding, more subtle variations appear. As such, any mathematical formulation was an approximation of nature, valid till a better approximation – that fit the observations better – is found. All knowledge is *ad hoc* and a transient representation of nature. Almost all cultures began their study of nature implicitly or explicitly with this premise and most continue with it. This approach allowed them to take up everything from complex architecture to accurate positional astronomy. This approach also relied extensively on mathematical representation, but was assumed to be an approximation. The biggest advantage of the pragmatic approach is that it provided a way around the suffocating hold of the religious approach to science and avoided the direct conflict with religious ideas that have marked the axiomatic approach to the study of nature.

Table 1. Different approaches to studies of nature

Approach	Period of dominance	Characteristics	Approach to observation of smoke on the mountain	Major achievements
Ad hoc approach	2 millennium BC to 5000 BC	Makes working objects based on perceived need	There is smoke on the mountain – avoid the region	Early technologies from stone tools to travel.
Religious approach	2000 BC to 1000 AD	Humans are taught required skills by divine intervention when humans are ready for it.	There is a divine smoke on the mountain – worship it	Stabilization of society.
Pragmatic approach	3000 BC to 1600 AD and continuing to date but at a lower scale	Nature works in logical and consistent ways that can be analysed. But any such knowledge is topical and good only for the situation in which it is applied.	There is smoke so there must be fire on the mountain	Clarity and mathematical precision in prediction of seasons to all aspects of human existence
Axiomatic approach	1600 AD onwards	Nature's working is consistent and universal and nature obeys all its rules under all conditions and has no exceptions.	The smoke on the mountain implies that: (i) There is dry inflammable material on the mountain. (ii) There is a source of heat that heated this material to the temperature where it caught fire.	Development of new technologies, simplified description of nature.
Logic-based approach	500 AD onwards but less prominent than axiomatic approach	Working of nature is logical and consistent that extends to common rules which work well. However, there is no admission of generalized universal laws.	There is smoke so there is fire, implying that there is inflammable material on the mountain.	Providing intellectual explanation for the working of the laws of nature.

During this period, a sense of autonomy amongst the learned results in elaborate observations of nature and mathematical modelling of the working of the universe. Epicyclical movement of planets and corresponding geometrical and algebraic ideas as well as measurements of the size of the Earth, etc. are typical exercises that were taken up during the period.

Axiomatic approach

This approach assumes that nature works in strictly logical way. It is therefore possible to understand nature by separating the different aspects of its working and studying them in isolated environments. The Greeks were probably the first to be obsessed with this idea. However, in the absence of good data – or even good pragmatic ideas – their axiomatic approach did not progress beyond the works of Archimedes and other Greek scientists. It remained alive only as notes of interesting ideas in forgotten or lost Greek texts and Arabic culture but did not find much favour in India. During this period, the entire set of ideas on how the universe has been seen to be working, are formalized and a demand for logical consistency is made on the working of nature. During the period, astronomers formulated ideas of gravity depending on early observational records of the pragmatic period. They then merged it with the realization of conic sections as the shapes of orbits and provided the first physical model of the solar system, and gave glimpses of our universe. Developments in physics and other fields opened the doors for multi wavelength and telescopic observations of the universe. Typical theoretical study involved idealized, simplified analysis of real physical systems, often simplified to fit into the mathematical capabilities of the period.

Logic-based approach

This approach assumes that the working of nature had certain underlying principles which are subject to analysis, but isolated mathematically formulated principles only have limited applicability. In reality nature is complex and not amenable to the classical axiomatic formalism. So while one can still create mathematical models of the working of a small aspect of nature, they will not be central to its understanding. The underlying physical ideas will be provided by specific assumptions valid for the particular problem being addressed. In many cases, the linguistic format may be more conducive for understanding nature. By implication therefore, the set of axioms and formalisms that explain nature will not be a finite set, but will consist of an open-ended vocabulary. This language will be precise in its definition of words and formulation of linguistic structure will have precision of consistency and structure. The words and grammar of the language will be traceable back to a set of rules.

The rules of modification for application to a local situation will be logical and intrinsically explanatory as well as subject to rigorous but descriptive or informal logic. This approach will subsume the pragmatic approach and will generalize the axiomatic approach, as it will have a visual impressionist approach to the behaviour of nature. Saturated by approximate correlation between theories and experimental data, astronomers began to appreciate that their early simplified analysis that allowed analytical solutions to observations no longer provide the complete description of reality; including more realistic information takes the problem beyond the capabilities of elegant analytical solutions, and theoretical studies are either approximated or simulated to provide better insights.

With the advent of formal mathematics, this idea of informal logic would expand to formal logic where propositions cannot be proven through basic rules or operation. The study of nature will put greater emphasis on geometry, analysis and logic whereas the classical, algebraic approach will have reduced applicability.

Comparison of different approaches

Some basic scientific understanding is evident and common to human development that arose before humans dispersed all over the globe almost hundred thousand years ago[1]. They include cave making, cave painting and possibly some basic ideas of early religion. They are common in many early cultures in different parts of the world. Some form of language was probably extant much earlier[12], but the diversity within these languages is significant and suggests that a large fraction of the development of language was local to different regions[13,14].

However, early approaches were a mix of *ad hoc* and pragmatic. For our analysis of evolution, we will not delve into an *ad hoc* since it naturally progresses into pragmatic approach with the advent of education. Similarly, the religious approach is a dead-end of intellect as the exploration of ideas, theories, images and myths about this superhuman and his creation have commanded a significant amount of human intellectual resources and continues to do so. However, we shall ignore this line since it does not even attempt an analytical approach to understanding nature.

Most cultures have used this approach in understanding the working of nature: for example Egyptian science[15] and Indian science[16]. The most exhaustive of these studies is a series of volumes by Needham[17] which has discussed Chinese science at length. These studies suggest that the pragmatic approach was adopted according to continuing advancement in mathematical astronomy driven by cultures and people not particularly sensitive to religious approach. However, their focus remained on identifying and applying new and needed technologies for general well-being. A specific idea of classifying the working of nature was not focus of these studies. Their classical approach was to classify nature into four or five basic entities namely solid, liquid, gas, energy and sky. Amongst the most detailed approach is the one explored by the Indian civilization around 600 BC. This included classifying nature not only into five basic properties and assigning various attributes to the same (Figure 1) that appears in the book *Vaiseshika of Kanada*[18–20]. For a more general discussion on Indian philosophy and philosophy of science see Sarukkai[21].

The sophistication explained that various properties of matter and their changing form including mechanics etc. did not need intervention of unknown forces in the working of nature. However, it was not extended to search for underlying physical laws that governed the universe. No attempt was made to understand the underlying principles, routine situations or application of a technology. Hence fields like classical mechanics (analytical study of mechanical properties of matter in isolated systems) and thermodynamics (which arises from study of gases) were never pursued and would probably not have been pursued at all. This is interesting because mechanics and chemistry were fairly advanced and Chinese even harnessed steam energy. They built everything from the Great Pyramids and Taj Mahal and steam engines, but did not worry about the roots of basic properties of nature. This narrow focus put rather stringent limits on how far this field would have progressed.

The axiomatic approach has been the most perceptive of all the approaches and is often assumed to be the beginning of the scientific revolution and the beginning of scientific approach to life. However, axiomatic method would not have worked in isolation. It needed long traditions of meticulous observations that predated the Renaissance period when this method flourished. Without a proper understanding of nature, axiomatic method would have failed – as it did in the early Greek period. Its primary success was its application in all aspects of the working of nature. It has not succeeded much in technological innovation as earlier approaches had been ignorant of some major aspects of human studies. Starting with

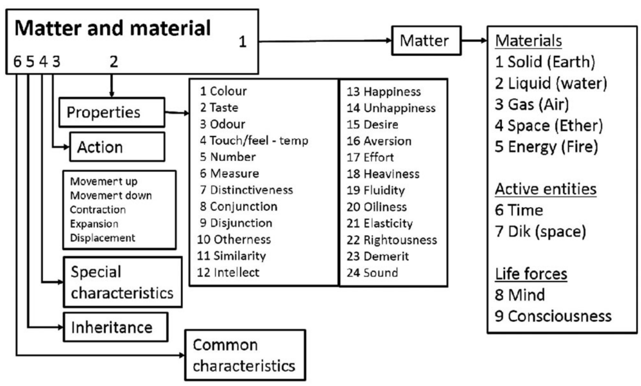

Figure 1. Organization of nature in Indian philosophy.

Galileo's astronomy to Newtonian mechanics, it led to the field of thermodynamics and recognition of electromagnetic fields and particle physics along with several allied fields. At the same time, it was responsible for phenomenal increase in technologies. However, as seen below, we seem to have reached a plateau in these studies and this approach seems to be self-limiting.

The difference between the logic-based and pragmatic approach is that the logic-based approach assumes that mathematical precision is consistent *within an underlying, objective physical framework*. While pragmatic approach demands simple predictability of events based on formulations, logic-based approach insists on underlying logical consistency which may or may not be amenable to formal mathematical approach. This in turn would permit analysis of complex situations where several of the axioms were at play simultaneously. It differs from axiomatic approach as it does not demand a physical basis for the validity of a formulation, to be consistent and accurate in terms of defining an environment.

The pragmatic approach was highly successful in its understanding mechanics. However, adaptation of mechanics by axiomatists required concepts such as friction, centripetal force, etc. to be consistent. For example, friction itself arises from electrostatic forces and any axiomatic study of friction must begin with intermolecular forces. However, the most common approach to using friction is to assume a (measured) *ad hoc* parameter called the coefficient of friction. Such broad and working generalizations pervade all aspects of science. Mostly physics does not begin with atomic structure, but with the idea of 'bulk matter' – which is a pragmatist's approximation lacking the purity demanded by an axiomatist.

Even then, civilizations that were pragmatic in their approach, also worked on mathematical formulation where possible, since axiomatic approach has the elegance of simplicity. While studying mathematics they found that purely formal approach worked well. For astronomy the logic of consistency retained their validity over long periods of time. For example, without gravity or need for Heliocentric or Geocentric models, using mathematical formulation permitted Indian pragmatists to extend their studies significantly. Using the concept of *prakruti swabhav* (compulsion based on one's nature), each planet's controlling equation was satisfactory. Indians were so committed to pragmatic ideas that even while invoking the ideas of epicycles in planetary motion, they used mathematical formulations without worrying about underlying axioms as Europeans did. So while Europeans were trying to define circles within circles, fitting their radius and trying to explain why this happened, the Indians were quite satisfied with the mathematical formulation and the relative locations of planets where retrograde motion needed to be included. They did not significantly extend their studies to more classical systems and these were left to more *ad hoc* experimentation.

The absence of search for axioms and satisfaction with pragmatism meant that the description of nature such as astronomy reached a gradual progression and soon hit a plateau. Mechanics was left to technological development and was isolated from developments in mathematics. Hence, while these fields made solid progress using the concepts from mathematics, they did not attract intellectual studies on the reasons why these mathematical models worked and it remained a logic-based delight. They built large and complex architecture and technologies, which would have needed an understanding of the underlying mathematics, but they did not try to figure out the core of *prakruti swabhav*.

Hoodboy[8] has discussed issues related to religion and science (in the context of Islam), the pragmatic Muslim approach to science and the western axiomatic approach to science. He points out that the fundamental nature of axiomatic science is its very secular nature, in the sense that, it deals with worldly matters and accepts no authority. Even at the peak of its success in the Arab world till 13th century before it was overwhelmed by orthodoxy, the subject remained elitist for the following reasons in the context of Islamic or Muslim science[8]:

(1) The applications of *ad hoc* science were limited and hence did not enthuse artisans and tradesmen at large.

(2) Since it progressed by court patronage, the focus of science practitioners was to please the court rather than design new devices.

(3) It never found its way into the teaching curriculum at large and was restricted to a few schools.

(4) The authors of great works went out of their way to restrict the readability of their writing, so that commoners did not get to comment on it or access it.

This is probably true of all cultures that practiced pragmatic science. Hoodbhoy[8] also discusses the specific social structure of the Arabs and Muslims who had taken the studies from the Indian culture, did not take it to the next level of axiomatic approach in which the Europeans excelled[8].

The axiomatic method would not have worked in isolation. Without a massive amount of universal understanding of the nature developed by the pragmatists, the axiomatic method would have failed – as it did in early Greek period. One example of this is as follows. Matter has mass and hence is subject to gravitational pull. Hence, humans stand on earth due to gravity. A corollary of this would be that insects crawl on humans also due to gravity. However, this is clearly not true – for insects to be on humans, you need electrostatic forces.

The Europeans in the Renaissance period absorbed the results of the pragmatic approach to mechanics and axiomatic approach to mathematics also learnt of the ancient axiomatic traditions of Greeks (Arab records) and revived them with vigour even as they heavily borrowed from logic-based and pragmatic approach of the Asians. Purely axiomatic approach of the Greeks had not got very far – it needed crucial inputs from the other methods of study.

The result of these developments was that they had a rich field of data, experience and mathematics, which they converted to axiomatic sciences. Since nature responded well to these axioms founded on earlier pragmatic studies, Europe made quick progress in the understanding of nature and our capability to manipulate it. With a commitment to experimentation for validating their axioms, they soon discovered thermodynamics and electromagnetism – fields that had been completely missed by the pragmatics – even though they had extensive experience in metallurgy.

However, as we begin to study inherently complex systems where multiple axioms work simultaneously, neither *ad hoc* localized formalism nor the superposed formulation of multiple concepts together would succeed. Science is also looking at systems in real environment, which puts additional limitations on the development of clear axioms to study nature.

The approach that is now gaining ground is that, the working of nature has underlying principles, which can be analysed and described in descriptive form. However, these are not general essays, but the terminologies used are precisely defined. These are necessary and sufficient to describe some aspects of nature. It is therefore necessary that the words and grammar of the language should refer back to a set of rules. The rules were logical and intrinsically explanatory, as well as, subject to rigorous logic and amenable to mathematical approximation. However, mathematics may not be the best way to describe them *in view of the inherent complexity.* Hence it is impossible to prove 'facts' and the best we can do is to state that something seems true based on available experimental and simulated data. This approach ran parallel to axiomatic approach and provided analogy for mathematical representation. However, with increasing complexity of problems being addressed, this is now the principle means of understanding nature, with simulations replacing formal proofs. Removing mathematical description brought in some much needed approximations in the description of nature.

Godel complexity and the limits of axiomatic approach

There are two primary reasons why the axiomatic approach will be self-limited. Detailed studies of science have made it clear that formalizing science in the mathematical sense is not easy and may even be impossible[22]. Axiomatic approach, therefore will not be able to encompass the entire set of results in physical sciences. The natural reality in many cases is inherently complex and driven by fractals and chaotic undercurrents, which cannot be fully predefined in an axiomatic manner. Also, bulk studies of matter in particular are vulnerable to interferences and cannot be modelled from first principles, thus, operative simplicity will need to be employed depending on the scale of the problem and the detailed need for its understanding in a specific situation. However, even if this barrier were to be overcome, Godel's incompleteness theorem would limit the axiomatic approach.

The Godel Wall arises from the work of Kurt Godel, which shows that a purely axiomatic system will have incompleteness problem. Such systems will have to accept facts that it cannot prove. The second limitation arises from the fact that systems are now studied in their full, complex and more in *in situ* and realistic environments. These studies struggle to prove its validity from first principles and rely on non-deniability, through experimentation and simulation. It also makes it essential to explore fundamentally different ideas about the organization of nature.

The fact that the axiomatic approach will be saturated, is clearly demonstrated by Godel's incompleteness theorem which states that, any axiomatic system will have statements that even though true, will not be provable within the system. Several authors have discussed the limitations and applicability of Godel's theorem in other fields[23–26], which shows that any axiomatic approach is self-limiting. The result is that, sooner rather than later, the axiomatic approach will be manifestly incomplete in the sense that, it will not be able to prove all statements that are true. However, this approach to study nature is far more powerful than any earlier approach. But, as systems become increasingly complex, the axiomatic approach will begin to reach its limits. It will no longer be possible to explore nature purely on the basis of axioms, since we will begin to encounter systems whose complete description will no longer be provable within the axiomatic system. Future studies will begin to increasingly rely on pragmatic formulations, governed by experiments and turn to a more logic-based approach to understand nature.

This severely limits the reach of axiomatic science as long as they claim to represent all aspects of nature. A theory of everything would be a formal system where Gödel's theorem applies, and in such a case, the system will not be able to provide proof for all that is true even within itself. We will have to accept that, in so far as we accept that the basic axioms of science form a total system of description of the physical world, we will also have to accept that it will not be complete, in that, it will not be able to prove everything. The alternative is to assume that the axiomatic system is not complete in the sense that, there will be systems which it cannot establish from within its set of axioms. In that case, science will never have a complete set of rules and even though its rulebook will be self-consistent (and not internally contradictory), it will not be complete. A system can be consistent, but not complete and amenable to analytical studies[25]. Under these conditions Godel's theorem does not apply. However, these systems then will continuously need additions of axioms to explain the system with increasing complex rules for adaptation, making it unwieldy.

Also, in case of physical systems, complexity of such system does not help the axiomatic approach, where too many axiomatic processes work simultaneously. All realistic systems are complex systems and not amenable to the kind of simplification crucial for mathematical description. Experimentation, simulation and 'true to the best of our knowledge' approach will dominate.

The result will be a merged field, where axioms will not be proven, but will be shown to be non-deniable. However, the validity of these descriptions of the governing principles of nature will have to be proven by non-falsifiability with computer modelling and extensive testing. A concept will be true because it cannot be falsified under any situation we can think of and simulate.

Physics is relatively idealized and isolating the systems is possible and hence its growth along axiomatic lines is possible. This is not the case with biology which, at best can use axioms from chemistry, but still needs to be validated and the interplay of multiple axioms simultaneously, is difficult to judge or generalize. The axioms of chemistry themselves are generalized concepts from atomic physics since it is not possible to revert to atomicity for every extension of knowledge. It is logician's delight.

The future of science therefore is drifting further away from purely axiomatic approach, as various subjects reach the Godel Wall. One can argue whether the Godel wall is a limitation of human mind or whether the complex systems (with their intrinsic tendency to be chaotic) are difficult to define axiomatically. String theory, for example claims legitimacy, based more on a logical approach than axiomatic proof. Cosmology is another field where the Godel Wall arising from lack of knowledge of acceptable axioms – has resulted in logical approach to science. The usage of cellular automata and its related modelling[27] is an example of this changing emphasis on science, where again simulation seems to be the way of validating (or discounting) a scientific hypothesis.

In some sense, this is also a reflection of the human brain. Designed to survive in the wild with three requirements – to eat, not be eaten and reproduce – human senses are hierarchical with visual sense having the highest priority. This predisposes the brain to visualize and accept a visualized picture as an acceptable expression of the working of nature. Any visualization eventually becomes more logic-based and accepts non-falsifiability within the reach of experience as satisfactory proof of validity. So while experiments remain the final arbiters in any rational analysis, the axiomatic approach is easily replaced by logical or even pragmatic approach.

Hence, the future of science is increasingly logic-based and pragmatic. Technologies will work entirely based on logic. The basic argument is that nature obeys a set of rules and they can be combined into a machine, which in some ways makes our life more comfortable or interesting. Hence the exponential increase in knowledge may have been triggered by axiomatic approach but it is only a transient state, in the long march of humans to understand and master nature for their personal gains.

In Figure 2, we have attempted to plot the path of growth of science. It is a purely intuitive and off-scale plot to aid thinking. It discusses the fields of science which were discovered by various approaches and the broad geographical regions that dominated these fields. It suggests that the axiomatic approach is reaching its limit after a strong growth for the past 400 years. We have suggested that the logical approach will probably not be as spectacular. This statement is made based more on the experience that, any new system of knowledge or approach takes some time before it matures to a level where it can contribute significantly to our understanding of nature and will have to run parallel to the axiomatic approach for some time, especially in physics, even though the logical approach is already visible in other fields of science. Another reason why logical approach may not gather exponential growth is that, the hardware and to some extent the software expansion rate is reaching its own limits[28], unless new generation of ideas such as quantum computers or new approaches like the cellular automata[2], or such fundamentally different approach arises.

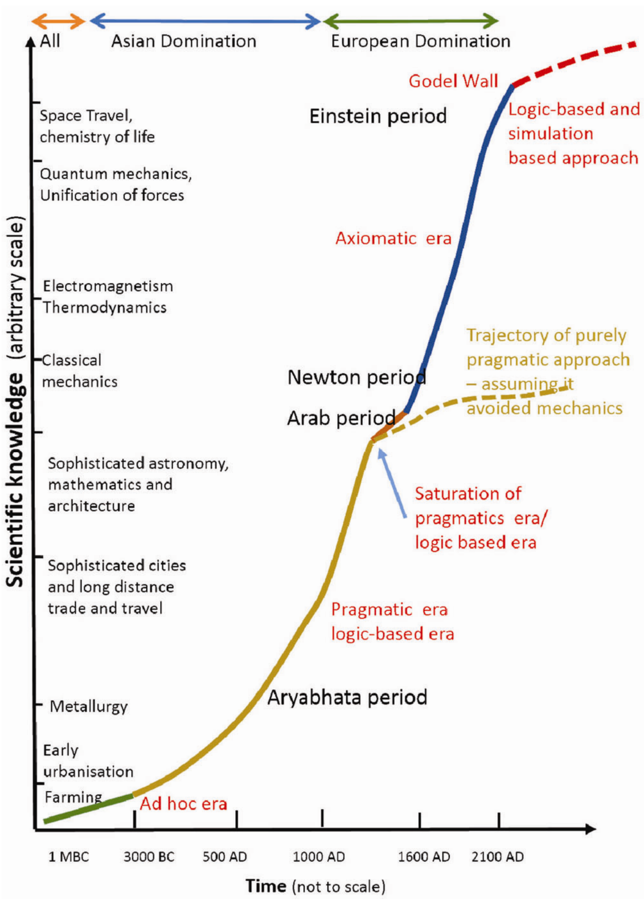

Figure 2. Sketch of the most dominant approach to science over human civilization.

We are now on the threshold of the post-axiomatic phase, which will require fundamental restructuring of our thinking about nature and science and their mutual complementarity. With no axioms to validate a hypothesis, we will have to redefine how we validate experimental results. We will have to have new criteria of reliability of results and probably include definition of the scope and limits of the discovered truth or invented technology.

We also need to retune our emphasis as we transit from iron–silicon and pure semiconductor age to carbon-based age, which promises access to far more complex structures of matter than what we have been used to. This will change the rate at which we expand our base of science and technology. In Figure 2 we have shown the growth to be plateaued, but that may well be a short term phase. We may as well restart an exponential phase of development thereafter. The future orientation for funding of science will have to worry about these issues and future institutes that emphasize applied research will have to focus on these aspects of the coming phase of science.

Conclusion

We have analysed the evolution of human studies of nature from early *ad hoc* approach to formal scientific methods. The latter can be of three kinds, pragmatic, axiomatic and logic-based approach. We have discussed the relevance and important contribution of each system. We then showed that the pragmatic and axiomatic approaches, though highly successful in their times, are at the limit of their ability to explore nature, and the coming generation of scientific studies will adopt more logic-based approach, where formal proofs from first principle will no longer be possible and simulation and experimentation will be primary methods of building our knowledge base about the working of nature.

1. Vahia, M. N., Evolution of science I: evolution of mind. *Curr. Sci.*, 2016, **111**(9), 1456–1464.
2. Conard, N. J., A female figurine from the basal Aurignacian of Hohle Fels cave in south Western Germany. *Nature*, 2009, **459**, 248–252.
3. Iaccarino, M., *Science and Culture*, European molecular biology organization. *EMBO Rep.*, 2003, **4**(3), 220–224; doi:10.1038/sj.embor.embor781
4. Narasimha, R., The Indian half of Needham's question: some thoughts on axioms, models, algorithms, and computational positivism. *Interdisciplin. Sci. Rev.*, 2003, **28**(1), 1–13.
5. Ganeri, J., *Indian Logic: A Reader*, Routledge, London, 2001.
6. Wilder, R. L., *The Axiomatic Method, The World of Mathematics* (ed. Newman, J. A.), George Allen and Unwin London, 1960, vol. 3, pp 1647–1667.
7. Culotta, E., On the origin of religion. *Science*, 2009, **326**, 784–787.
8. Hoodbhoy, P., *Islam and Science, Religious Orthodoxy and the Battle for Rationality*, Zed Bools, 1991.
9. Wade, L., Birth of moralizing gods. *Science*, 2015, **349**, 919–922.
10. Boyer, P., Religion: bound to believe? *Nature*, 2008, **455**, 1038–1039.
11. Ball, P., Triumph of the medieval mind. *Nature*, 2008, **452**, 816–818.
12. Dediu, D. and Ladd, D. R., Linguistic tone is related to the population frequency of the adaptive haplogroups of two brain size genes, ASPM and Microcephalin. *Proc. Natl. Acad. Sci.*, 2007, **104**, 10944.
13. Dediu, D. and Levinson, S. C., On the antiquity of languages: the reinterpretation of Neanderthal linguistic capacities and its consequences. *Front. Psychol.*, 2013, **4**, 1.
14. Evans, N. and Levinson, S. C., Myth of language universals: language diversity and its importance to cognitive science. *Brain Behav. Sci.*, 2009, **32**, 429–492.
15. Chagett, M., *Ancient Egyptian Science*, American Philosophical Society, vol. 1–3, 1995.
16. Subbarayappa, B. V., *Science in India: Past and Present*, Nehru Centre, Mumbai, 2007.
17. Needham, J., *Science and Civilization in China Volume* (There are now 7 volumes in the series), 1954; http://www.nri.org.uk/science.html
18. Umesh, M., *Nyaya Vaiseshika: Conceptions of matter in Indian Philosophy*, Bharatiya Kala Prakashan (reprint of earlier edition of 1936), 2006.
19. Debasish, C., *Vaiseshika Sutra by Kanada* (*in English*), D K Printworld, New Delhi, 2003.
20. Jagdish Chandra, C., *The Hindu Realism; Being an Introduction to the Metaphysics of the Nyaya–Vaiseshika System of Philosophy*, reprinted by General Books, 1912; www.General-Books.net.
21. Sarukkai, S., *Indian Philosophy and Philosophy of Science* (ed. Chattopadhyaya, D. P.), Project of History of Indian Science, Philosophy and Culture, Centre for Studies in Civilisations, ISBN 81-87586-22-2, 2008.
22. Watson, W. H., *Understanding Physics Today*, Cambridge University Press, 1963.
23. Nagel, E. and Newman, J. R., *The World of Mathematics Volume 3* (ed. Newman, J. A.), George Allen and Unwin London, 1960, pp. 1668–1695.
24. Raatikainen, P., *Gödel's Incompleteness Theorems*. *The Stanford Encyclopedia of Philosophy* (spring 2014 Edition) (ed. Zalta, E. N.), 2014; http://plato.stanford.edu/archives/spr2014/entries/goedel-incompleteness/
25. Franzen, T., *Gödel's Theorem: An Incomplete Guide to its Use and Abuse*, A K Peters, 2005.
26. Franzen, T., *The Popular Impact of Gödel's Incompleteness Theorem*, Notes of the American Mathematical Society, 2006, **53**, 440–443.
27. Wolfram, S., *New Kind of Science*, 2011.
28. Markov, I. L., Limits on fundamental limits to computation. *Nature*, 2014, **512**, 147.

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