

Some thoughts on the Indian half of Needham question
Axioms, models and algorithms

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Summary

Much debate has taken place on the famous question raised at various times during the last several decades by Joseph Needham, regarding the failure of China and India to give rise to distinctively modern science while being ahead of Europe for fourteen previous centuries A variety of explanations have been offered in India for the failure mentioned in the above quote. Apart from those involving political, military or economic factors, these explanations have ranged from an (alleged) preference for idealist philosophies and an inward-looking, other-worldly culture, to the prevalence of a rigidly stratified social system. It is argued in this paper that while there may be some truth in many of the socio-cultural explanations that have hitherto been offered, they are in the final analysis not truly convincing for three major reasons: (a) the philosophical systems of India are diverse and not exclusively idealist, (b) at the end of the first millennium the sciences in India were in a relatively strong position in the civilized world of the day, and had indeed become very influential, and (c) (as the quote above from Needham admits) India (with China) was in fact ahead of Europe for fourteen long centuries before the European scientific revolution — and there is no evidence that the explanations offered were not operative in that long period.

The proposal in this paper is that it would be more useful to approach the question by looking at what happened in Europe in the 16th century and later as the manifestation of a *European miracle*. In order to understand the roots of this miracle it is important to study earlier developments in Europe, say during the 12th to 15th centuries. It is now well known that several Eastern inventions travelled to the West during and after the Crusades. Among these were a variety of technologies from China, and the new numeral and mathematical inventions that went from India (both through creative West Asian intermediaries). The renowned mathematician Hermann Weyl wrote in 1929: Occidental mathematics has in past centuries broken away from the Greek view and followed a course which seems to have originated in India and which has been transmitted, with additions, to us by the Arabs; in it the concept of number appears as logically prior to the concepts of geometry. Indeed the history of mathematics in India can be interpreted as indicating the occurrence of a mathematical revolution heralded by *_rya-bhat**a*, and leading in the next several centuries to the development of the Indian numeral system, algebra, techniques for solving both linear and quadratic determinate and indeterminate equations, and the germs of the calculus. These new mathematical techniques travelled West over the course of centuries and appeared to have played a decisive role in the mathematization of science that was such an essential ingredient of the European scientific revolution — in ways that still have to be more completely studied.

The Needham question then rephrases itself to ask why the Indian mathematical revolution did not lead to a corresponding distinctively modern scientific one. One reason could be that it was not accompanied by the generation of new technologies — or their absorption from elsewhere (e.g. China). (Quite possibly no social, economic or political need was felt for them in India at the time.) But there appears to have been another fundamental philosophical reason, illustrated by the totally different approaches to science taken in classical Greece and classical India. By a detailed comparison of two texts in geometry (the Indian *_ulba-s_tras* and the Greek Euclid) and in astronomy (Ptolemy and *_ryabhat**a*), it is proposed that, in a useful over-simplification, the Greek approach may be thought of as that of axiomatizers and model-makers and the Indian approach as that of pattern-seekers and alorisers. The style of the Indian intellectual approach indicates a deep suspicion of axioms and models, but great ingenuity in handling numbers and discerning patterns (for example in the motion of heavenly bodies). It is suggested that the European scientific revolution, which may be traced to Copernicus, Galileo and Newton, came about in part because of a powerful fusion of the ideas of model-making and algorithms. It is also argued that the distrust of universal axioms and models in Indian logical systems appears to have been philosophically justified, and may be said to have been vindicated by 20th century developments in quantum and classical mechanics and in logic (e.g. wave-particle duality, G del s theorems, deterministic chaos). At the same time the use of what to a classical Indian logician will appear as a somewhat less fastidious approach in Europe towards understanding nature led to unreasonably and unexpectedly spectacular successes in the development of science there.

We can say that European model-making could not progress without the mathematical tools whose roots can be traced to India, and similarly that Indian science could not progress without the model-making abilities of the West. The distrust of models, while not philosophically unjustified, turned out to be historically expensive for India.

A good place to begin this lecture is to ask ourselves whether we now live in an age of revolutions. We may be on the threshold of a biotech or genetic revolution. We are in the middle of an information technology revolution (— or at its beginning or end, depending on one s degree of technological optimism). We have had a green revolution, but are now told that it may have spent itself — at least the variety that we had in India. There has been much talk of the white revolution, and other similar ones of various hues and shades.

Note that these revolutions we speak about now are so often scientific or technological; they are no longer national or ideological, like the French, Russian or socialist types. We are now at least as worried about the digital divide as about any ideological divide. Here is proof, if it were needed, that science and technology now affect our ordinary ways of living in extraordinary ways, and have become a major force in the civilization of the planet. One may admire, or dread, what science can do; an

admirer may have pet technological dislikes, and a technophobe, even as he keeps busy rubbishing technology, may cheerfully use computers and cell-phones and airplanes, and all those other wonderful toys and tools that the technology bazaar offers him. Whatever one's views on science, it has become impossible to ignore it, and difficult to be neutral about it. After all, according to the Nobel Prize winning economist Robert Solow, half the economic growth of a nation today is due to technical factors.

Indeed, as a scientist myself, I know that all of us tell each other how we Indians missed the bus on revolution A, and should make sure we do not make the same mistake on revolution B. A very good point indeed, but it would seem worth analyzing how these revolutions have occurred, in particular the grand parents of them all, namely the scientific and industrial revolutions.

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These revolutions began in the Europe of the 16th to 17th centuries, and spread first to North America; in the 20th century they diffused across to Asia. (For our purposes here, a revolution in a system is a change that takes place in a time relatively short compared to the time scales of change in that system before the revolution. I believe it would be better to call the phenomenon a water-shed, but the word revolution has become standard.) The first effects of these revolutions on India were historically painful: they led to the decimation of the famed textile and metallurgical industries of the country, accompanied by a European political domination that was supported — indeed often driven — by superior military and civil technologies. As Headrick points out (in his book *The Tools of Empire*, Oxford 1981), technology made it feasible for European power to spread where it had earlier been impossible for it to penetrate (e.g. because of disease, as in Africa); in other cases it made colonial expansion very cost-effective and affordable (as in India). The net effect was that, by the beginning of the first World War in 1914, over 84% of the world's land area was under European domination, and the great and ancient civilizations of Asia had been reduced to formal or informal colonies (to use Ian Inkster's phrase).

Among the first Indians to have realized that the rapid expansion and consolidation of British power by early 19th century was not the isolated success of one more plundering raider from across the borders, but that it represented the advent of a new cultural force based on novel knowledge systems, was Raja Rammohan Roy (1772-1833). This realization lay behind his deep concern about the poor state of the mechanical arts in India (as he called them), which was coupled with his understanding of the need for a transformation of Indian society and the importance of learning English to gain access to the new knowledge. He had already an integrated vision of what needed to be done in education, society and technology, and was probably the first person in today's third world to wonder about the nature of the industrial revolution then sweeping the West. According to Kisorichand Mitra, a younger contemporary of his, Roy went to England (in 1830) because He longed to see . . . the country of the Lockes, of the Bacons, of the Newtons, of the Hampdons and of the Watts. Note the conspicuous absence in this list of the so-called empire-builders like Clive and Hastings; Roy appears to have realized that behind the war-fighters he had seen was a world of new ideas and thinkers in science, technology and philosophy. Elsewhere he spoke of the perfection of

the mechanical arts in England, and even advocated the settlement of Europeans in India to help introduce their knowledge into the country. The questions that he raised for himself then have since concerned the growing community of scientists and engineers as well as political and social leaders all over the East.

The issue of the new knowledge systems that arose in Europe has now acquired a remarkable intellectual and philosophical dimension, following the monumental work of Joseph Needham on science and technology in ancient China. Needham has carefully documented the extensive technological achievements of the Chinese civilization, often pre-dating Western developments by centuries. It is enough to note here that, among the inventions of the Chinese were not only the famous trio of the printing press, gun-powder and compass, but innumerable others including paper, rockets, the (clock) escapement mechanism and silk. After a meticulous survey of these and numerous other instances of eastern inventiveness, Needham pointed out:

With the appearance on the scene of intensive studies of mathematics, science, technology and medicine in the great non-European civilizations, debate is likely to sharpen, for the failure of China and India to give rise to distinctively modern science while being ahead of Europe for fourteen previous centuries is going to take some explaining.

And he wondered about

. . . how Galilean science could come to birth in Pisa but not in Patna or Peking.

There have been very stimulating surveys of Indian science and technology too in recent years, but nothing that even remotely matches the scale, scope and magnificence of Needham's effort. Nevertheless, as I have already mentioned, the question now associated with Needham's name has plagued many Indian scientists and leaders for long, and there have also been efforts to explain, or analyse, why the scientific and industrial revolutions did not (or even could not) take place in India. Some favourite explanations, going back to P.C. Ray, the great chemist, are based on the inequities of the caste system and the idealist philosophies of India. The Marxist philosopher Debiprasad Chattopadhyaya, while claiming that the world's first natural scientist was Uddalaka Aruni who appears in the Chandogya Upanishad, went on to argue that the factors that Ray highlighted created an intellectual climate inimical to the growth of modern science.

As an aside, it is interesting to note that Needham finds it so easy to make the parenthetical assertion about the great eastern civilizations having been ahead of Europe for so long; late colonial historians would of course have been shocked by the assertion, and so I suspect would the considerable number of modern Indians brought up on the view of the likes of Macaulay and Mill. Earlier European observers, on the other hand, would have found that Needham was only echoing a widely-held view of their own times.

A catalogue of the various socio-cultural explanations appears in Box 1.

Box 1.

POSSIBLE REASONS WHY THE S&T REVOLUTIONS DID NOT OCCUR IN INDIA

- 'Idealist', 'speculative' philosophies
- Inward-looking, other-worldly culture
- No 'Protestant ethic'
- Social rigidity, caste system, lack of professional mobility, no cross-fertilization of ideas
- Weakness in observation, data-keeping
- Relative insularity: no foreign travel
- Inadequate public patronage
- Conflict between science and religion
- Civilizational complacency
- Oral traditions, resistance to documentation, closed education systems
- Inherent cultural tendency to live with contradictions

While there is some truth in many of the explanations listed above, there are serious difficulties as well. A major one is that the philosophical explanations in the list do not recognize the diversity of Indian civilization, and in particular its philosophies. Thus, while one may argue that Vedantic philosophy is idealistic or speculative, one must remember that there were many philosophical systems in India: the S_khya, Ny_ya or Vai_eshika systems cannot be accused of being anti-science. There was a vigorous materialist school as well (known as L_k_yata). Similarly, while the impression persists everywhere in the world that Indian culture is inward-looking and other-worldly (following the German sociologist Max Weber's analysis), we must remember that this could not have been true for the vast majority of the population. India is also the land of Kaut*ilya's *Artha-__stra* and V_tsy_yana's *K_ma-s_tra*, and Indian merchants have been entrepreneurial for thousands of years (from Indus Valley days, ca. 2000 BCE). Protestant movements in India are almost part of the mainstream (!), as the ancient history of Buddhism and Jainism shows, for example. Similarly, while it is true that the Indian caste system has been there for centuries, survives to this day and has undoubtedly inhibited mutual reinforcement of science and technology, it has been less rigid than is often thought, and social stratification elsewhere in the world was not always more dynamic or flexible than here. As for relations between science and religion, there were clashes between rationalist and conservative views (e.g. _rya-bhat**a and Brahma-gupta, 6th and 7th centuries CE), but the conflict never reached the intensity of Western violence (as e.g. when Bruno was burnt at the stake for his irreligious beliefs). Incidentally, while on this subject, we need to recall that the great star of the scientific revolution, Isaac Newton, spent far more time and wrote far more words on theology than he ever did on science.

The second difficulty with these explanations is that they ignore the presence of strong scientific traditions in India at different periods in our history. For example, the 11th century Spanish-Arab astronomer Said al-Andalusi said,

Eight peoples have interested themselves in the sciences: the Hindus, the Persians, the Chaldeans, the Hebrews, the Greeks, the Romans, the Egyptians and the Arabs. The premier nation among these in the sciences is that of the Hindus.

This comment was made only five centuries before the scientific revolution in Europe may be said to have begun; and there were others who said similar things at the time. One could argue that modern science dates from the 16th and 17th centuries and that it represents such a fundamental historical departure that the pre-revolution position of science in India was rendered irrelevant. That however would be inconsistent with the view of many Western scholars who insist that the Greeks invented science (which for example is the sub-title of a recent essay by Lewis Wolpert in the well-known British magazine *Nature*). This statement could probably be justified if the scope of the word science is suitably restricted. Thus we may ask: is science systematized, consensible knowledge purporting to organize reality (as Indians and many other civilizations have tended to think), or is science a quest for the ability to predict the behaviour of nature with the use of the fewest possible universal principles, laws or models? If the former, science was certainly not invented in Greece; if the latter it might have been, but then in periods when the quest for such intellectual minimalism begins to look unfruitful — as it must have done in the Europe of the Middle Ages — progress may become impossible. (And pre-Darwinian biology would not be science at all.) It seems certainly true that the Greeks had a remarkably special way of thinking about nature which characterizes their best scientific work. However, as we shall discuss below, the Greeks often got carried away by their philosophies and models. As Kitto remarks, Greek philosophy sought for uniformity in the multiplicity of phenomena, and [this] desire . . . led to guess work and neglect of fact in the attempt to frame a comprehensive theory. . . . As Daremberg says, the philosophers tried to explain nature while shutting their eyes (*The Greeks*, p.190). Francis Bacon (16th c. CE), the patron-saint of modern science, was scathingly critical of the Greeks.

The third difficulty is that for nearly 1400 years after these fundamental developments in Greece (as our quote from Needham recognizes), European science was by and large barren; no great advances — certainly in terms of fundamental ideas — were made in what in fact have come to be known in Europe as the Dark Ages. This was incidentally a period that was a Classical Age for India — in spite of all the reasons listed in Box 1. Many favoured explanations would seem to have been operating during that creative Indian period as well, suggesting that we must look elsewhere to find answers to Needham's question.

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The standard explanations may thus not be convincing, but the Needham question cannot be brushed under the rug. I would like to propose that it may be far more rewarding to approach the question from a very different point of view. Namely, instead of asking why India and China did not give rise to modern science, we need to ask how it happened that Europe did so. Given the long Dark Ages that Europe went through, it is in fact more appropriate to think of what happened there in the 16th century and later as the *European miracle* (just as we have in the last fifty years come to talk about the East

Asian miracle, for example). What was it that triggered the great and brilliant scientific revolution of the 16th and following centuries? To answer this question it is necessary to look at the period immediately preceding *the birth of modern science*. For example Paolo Rossi, in his book of the same name, by and large examines the period 1500-1700 (more precisely (:2) he dates the revolution as having occurred in the period of 160 years between the publication of *De Revolutionibus* by Copernicus in 1543 and of *Opticks* by Newton in 1704). A far more interesting period to study from our point of view would be the three centuries preceding the revolution, namely 1200-1500.

That of course would be a vast project on its own, and needs badly to be undertaken right away. But there are some very interesting pointers. One such clue regarding the precursors of the revolution is to be found in a very interesting essay by Sir Ernst Gombrich (*Daedalus* 1998 Winter: 193-205, Eastern inventions and Western response). Gombrich says that it was the Western response to the technical inventions that reached Europe from the East that undermined and finally swept away the belief that, in Bacon's words, excluded all theory of Progress. This event would seem to have been an essential prerequisite to the occurrence of the scientific revolution in Europe.

One fascinating piece of evidence that Gombrich provides is a book published in 1471 by Giovanni Tortelli. As a student of languages Tortelli was concerned with words in current use deriving from the Greek. His analysis showed that many words could not be traced to Greek roots and so presumably came from inventions unknown to the ancient European world. Among such (apart from the other well-known ones we have already mentioned) were spring-driven clocks, the marine compass, the bombard, stirrups, watermill, cotton, silk, candle, the organ, falconry, gilding and spectacles. Gombrich also points out that several new inventions listed in one of the paintings of the period came from China. These not only included the famous trio of compass, gun powder and printing but also silk, possibly the watermill, the clock escapement mechanism etc. Gombrich points out that there were two important omissions in the painted list: one was the paper on which the list was written (which also came from China), and the other the numerals that listed them (which came from India).

Regarding that famous trio of inventions, Francis Bacon wrote in 1620:

Consider the force and effect of inventions which are nowhere more conspicuous than in those three which were unknown to the ancients, namely printing, gunpowder and the magnet. For these three have changed the appearance and condition of the whole world, the first in letters, the second in warfare and the last in navigation, and from these there sprang innumerable changes so that no empire, sect or star appears to have exercised a greater power and influence on human affairs than these mechanical matters.

And where did those mechanical matters come from? Here is what Samuel Purchas was writing, as late as 1625:

Others, therefore, looke further unto the East, whence the Light of Sunne, and Arts, have seemed first to arise to our World; and will

have Marco Polo the Venetian above three hundred yeeres since to have brought it out of Mangi (which we now call China) into Italy. True it is, that the most magnified Arts have there first been borne, Printing, Gunnes, and perhaps this also of the Compasse, which the Portugals at their first entry of the Indian Seas found amongst the More, together with Cards and Qudrants to observe both the Heavens and Earth.

It is therefore clear that in the centuries just preceding 1500 a large number of technical inventions came into Europe from the East, in particular from China (through West Asia). The invention of invention that occurred in Europe around this time must have been triggered and inspired by the technological flood from the East.

The second clue comes from mathematics. This is important, for one of the most striking features of the scientific revolution was the mathematization of science. Galileo used mathematics to describe his experimental findings. Newton named his great and epoch-making book *Principia Mathematica Philosophiae Naturalis*: the Mathematical Principles of Natural Philosophy. Where did this mathematics come from?

It is here appropriate to quote from the renowned mathematical physicist Hermann Weyl, who wrote in 1929, in the preface to his pioneering book on quantum mechanics and group theory,

Occidental mathematics has in past centuries broken away from the Greek view and followed a course which seems to have originated in India and which has been transmitted, with additions, to us by the Arabs; in it the concept of number appears as logically prior to the concepts of geometry.

(He went on to say that, with the advent of group theory, the trend in mathematics was returning to the Greek standpoint.) Although the *Principia* is couched in the language of geometry, it appears that Newton did so because that was the proper way to do it (he was clearly in the grip of Euclid-worship); he almost certainly derived many of his results by quite different methods, involving algebra and equations, tools that were clearly imported from India and West Asia — and, of course, subsequently greatly improved in Europe. The tortuous trajectory of the spread of the Indian numeral system and associated methods of calculation — through West Asia, Islamic Spain and Jewish scholars and merchants to Christian Europe, involving such famous figures as Fibonacci (of the numbers fame) — has been brilliantly described by Georges Ifrah (1998 *The Universal History of Numbers*, Harvill Press, London).

We can see the impact of the key idea that Weyl puts his finger on — namely the *logical priority of number over geometry* — in the work of European scholars of the time, e.g. Descartes and his algebraic geometry. To simplify matters, one can say that, in the Greek view, if a was a length a^2 was an area (so the dimension increased from one to two); in the Indian view a was just a number — it could be a length, but so could a^2 be: the squaring was not necessarily a dimension-enhancing process. Once the view point has changed, one can see that the scope for mathematization increases enormously.

One can therefore argue that the long dark ages of Europe were broken with the help of the technical and mathematical inventions imported from the East. Europe came into contact with these through the violent conflict that took place with the Arabs during the Crusades. It is well known that at that time the Islamic adversaries of Christian Europe were the party more advanced in science. In fact Europe had often to rediscover some of its own Greek scientific heritage through translations that were more easily available in Arabic than in European languages — reminding one of what happened in India in the 18th and 19th centuries when British scholars were able to tell us more about Indian heritage in many areas than we Indians could remember ourselves (and to this day most of us keep learning about it in English rather than in Indian languages).

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Let us return to the question of what science really represents. Accepting for the moment a view of science as systematized knowledge, it is clear from a reading of eastern and western scientific literature that, at the very least, there are strong differences between different civilizations in the style in which they accumulate that systematized knowledge. These differences do appear to reflect deep philosophical differences in the approach to knowledge.

To illustrate, let us compare two approaches to geometry. One comes from the *_ulba-s_tras* dating perhaps to 7th or 8th century BCE, and the other from Euclid (3rd century BCE). The former is basically a manual of ritual geometry; its objective is to provide instructions on how to construct various fire altars that were part of Vedic sacrificial rites. Euclid on the other hand is a set of theorems in geometry derived from a set of axioms. Box 2 shows both the first page of the *_ulba-s_tras* and the set of five axioms from Euclid. The contrast cannot be stronger. The *S_tras* start with a listing of the units of length measurement, and go on to make a variety of propositions, including the so-called theorem of Pythagoras (who came much later, in the 6th c. BCE; incidentally it is not certain that he was in fact the original author of the famous theorem even in Greece). The result is stated in general terms, but (significantly, I believe: we shall return to this point) with explicit examples. No attempt is made to *prove* the result; it is clearly considered a valid conclusion — *a confident inference rather than a logical deduction*. The *S_tras* also consider the problem of how to construct a fire altar that is twice as large in area as a basic one. We know of course that this can be done by increasing the linear dimensions by $\sqrt{2}$, for which the *S_tras* give the (excellent) approximate value of 1.4142.

On the other hand Euclid begins by stating five axioms which he considers would be widely accepted and can provide a suitable basis for deducing, *purely by logic*, a variety of new results. Euclid avoids introducing *measures* of distance or area: in this sense he may be said to be *non-metric*. But the *S_tras* are *metric* from the word go. Euclid also states the theorem of Pythagoras, but derives it from the axioms that he accepts at the beginning of his book. The idea of $\sqrt{2}$ was a mystery to the Greeks, because it could not be expressed as a fraction. To the Indians on the other hand the question was one of finding an adequate approximation; there is no evidence that it caused any great intellectual agonization.

Box 2

Baudh_yana-_ulbas_tra

- 1.1 The various constructions of sacrificial fires are now given.
- 1.2 We shall explain the methods of measuring areas of their (different) figures (drawn) on the ground.
- 1.3 Now the measure of an *a_gula* 14 *anus* (grain of *Panicum milliaceum*); according to others, (it is) 34 *tilas* (*sesamum indicum*) placed broad side on. One small *pada* is 10 *a_gulas* each; one *pr_de_a* 12 *a_gulas*; one *pr(th_* and one *uttarayuga* 13 *a_gulas* each; one (big) *pada* 15 *a_gulas*. One *_s*_* measures 188 *a_gulas*; one *aks*a* 104 *a_gulas*; one *yuga* 86 *a_gulas*; one *j_nu* 32 *a_gulas*; one *_amy_* and one *b_hu* 36 *a_gulas* each. One *prakrama* equals 2 *padas* (30 *a_gulas*); one *aratni* 2 *pr_de_as* (24 *a_gulas*). But there are also instances of *pada*, *yuga*, *prakrama*, *aratni* and *_amy_* having different measures when these (words) are used as units of measurement. 5 *aratnis* (120 *a_gulas*) make one *purus*a*; one *vy_ma* also has the same measure (5 *aratnis*); and 4 *aratnis* (96 *a_gulas*) make one *vy_y_ma*.

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- 1.12 The areas (of the squares) produced separately by the length and the breadth of a rectangle together equal the area (of the square) produced by the diagonal.
- 1.13 This is observed in rectangles having sides 3 and 4, 12 and 5, 15 and 8, 7 and 24, 12 and 35, 15 and 36.

Euclid s Five Postulates (Axioms)

1. Given any two points, there is a straight line containing them.
2. Given any straight line segment, we can extend it indefinitely to both sides.
3. There is a circle with any given centre and radius.
4. All right angles are equal.
5. Given a straight line and any point not in it, there is exactly one straight line parallel to the given one and containing that point.

We might similarly compare the two great astronomers, Ptolemy (2nd c. CE) and *_rya-bhat**a* (5th c. CE). Ptolemy proceeds once again with a basic physical model in mind. The model is geocentric, and the planets move in epicycles, that is to say they trace small circles whose centres themselves move on other, larger circles. (The circle was a perfect figure for the Greeks, and all celestial bodies had therefore to move on circles, or circles on circles. As an aside, I cannot resist the temptation to say that this kind of Hellenistic perfectionalism (if one may coin that word) persists in the West to this day, as e.g. when Dirac made the famous statement, . . . it is more important to have beauty in one s equations than to have them fit experiment .) According to Aristotle space could not be empty (for nature abhors vacuum , he said). There was therefore a set of layered crystalline spherical shells each of which carries along one of the planets. (The shells had

to be crystalline, or a transparent solid, because one had to be able to see through to the stars.) The universe is finite, and outside the last shell is an unmoving Mover who rotates the shells. With these and some other hypotheses, utilizing observations made by himself and others before him, and by geometrical deduction appealing to Euclid for example, Ptolemy proceeds to derive an astonishing series of results on planetary motions.

Now *_rya-bhat**a* also uses epicycles, but by splitting planetary motion into a slow mean and a rapid epicyclic fluctuation superposed over it. It is very likely that the basic idea of epicyclic motion was borrowed from the Greeks, but the interesting point is that *_rya-bhat**a* does not speak of any underlying model at all. His book starts with a small introduction which describes a system by which he is going to express numbers, and a listing of the numerical parameters (including the trigonometric sines) needed to perform the calculations that form the bulk of the book. The values he chooses for the parameters are not justified in detail, but a series of instructions are provided on how to make calculations for prediction of planetary motions. (Such sets of instructions got to be called algorithms following the Iranian mathematician Al-Khwarizmi (9th c. CE), who transmitted many Indian mathematical ideas, along with his own very significant additions, to West Asia.) In the process however several brilliant new mathematical ideas are introduced by *_ryabhat**a*, but his objective is to make the calculations straight-forward and rapid. We could say that he invented the subject of algorithmic astronomy, and proceeded to present its first exposition in 499 CE.

Equally striking are the differences in style between our two authors. Ptolemy's work is called the *Almagest* from the title of its Arabic translation (whence it was first translated into European languages); and, as the title implies, the work is magisterial, monumental (nearly five hundred pages of dense prose). It is divided into 13 books, of which the first discusses and justifies the assumptions underlying the Ptolemaic model. The presentation is systematic, and indeed its rhetoric can be recognized in the scientific works written today. In contrast, *_rya-bhat**a*'s book, called the *_ryabhat**iya*, is terse, even cryptic; it is written in verse (there are a total of only 121 *_l_kas*), and is divided into four sections. A hand-written version of the work available in the Oriental Library at Mysore fills all of three sheets, and so can easily be slipped into a shirt pocket. The text was of course written so it could be memorized. But to *understand* it one needs a *guru* or at least a good commentary.

There are some conclusions we can draw from these comparisons. In the first place we realize that there appear to have been scientific contacts very early on between Greece and India, but what was borrowed or taken was extremely selective. One fascinating puzzle is why India apparently borrowed the *idea* of epicycles (but not either the underlying Ptolemaic model or its details), whereas it totally ignored Euclid, who made no impact at all; in fact he was not translated into Sanskrit till the 18th century! I consider this fact to be of fundamental significance, for Euclid has been virtually worshipped in the West: his *Elements* are next only to the Bible in readership over the centuries. Furthermore the Indian refusal to be impressed by Euclid survived centuries of Muslim rule in different parts of India, even though Islamic scholars were also admirers of Euclid. It almost looks as if the Indians took the view that (for example) the theorem of Pythagoras was a matter of observation and inference; I fancy that they did not think

that its deduction from a set of axioms was either useful or interesting, because they were skeptical about the reliability of the axioms. Similarly, although *ryabhat**a* does not say so, it would seem that he would have had great reservations (in retrospect most justified) in accepting the *physical* model of Ptolemy; after all Indians had no philosophical problems with the concepts of infinity, surds, vacuum etc., as many Greeks did. On the other hand *rya-bhat**a* finds in the *epicycle* a most convenient idea that helps to discern *patterns* in planetary motion and make computations, and proceeds to devise clever algorithms to carry out such calculations.

We may summarise the situation by saying that the Greek paradigm appears to have been *axioms* or *models* _ *logical deduction* _ *theorem* or *result*; the Indian approach seems to have been *observation* _ *algorithm* _ *validated conclusion*. (When we speak of models, here and elsewhere in this paper, we have in mind predictive, quantitative physico-mathematical models, not merely descriptive ones.) Contrary to popular perceptions Indian astronomers were very good at observation; the parameters in *ryabhat**a*'s algorithm were repeatedly fine-tuned over the centuries, as observation revealed discrepancies. (So *verification* was very much a part of the Indian approach.) We may also recall here the comment made by the 18th century British mathematician John Playfair, then a well-known professor at Edinburgh, now remembered as the author of Playfair's Axiom. (This formulated the notorious fifth axiom of Euclid in the form in which it is most widely used today, namely as it appears in Box 2.) Playfair was so impressed by the accuracy of Indian astronomical calculations that, in a review he published in 1790, he contemplated (but dismissed) the possibility that some ages ago there had arisen a Newton among the Brahmins . . . and a De La Grange . . . ; he preferred the explanation that accurate astronomical observations had been made in India as early as 3100 BCE. (I believe the accuracy that impressed Playfair so much was basically due to the willingness of Indian astronomers to tune model parameters, and their facility in carrying out such tuning. If the epicycles served only to seek and describe patterns in the planetary motion, there did not have to be a model that was either *true* or *false*; consequently the model was not something so sacred that its parameters could not be altered to suit observation. In other words, model parameters were not like e.g. the universal constant of gravitation.)

Incidentally *rya-bhat**a* had a profound influence on Indian astronomy, for almost as long as Ptolemy had on Western astronomy. And we could say that, as far as astronomy and mathematics were concerned, there was a rapid change in India between the middle of the 5th century and of the 7th century, i.e. between *ryabhat**a* and Brahma-gupta. If we accept the definition of revolution given earlier we can say that an algoristic or mathematical revolution occurred in India in those two centuries, or more precisely between the time of writing of the *ryabhat**ya* (499 CE) and the *Khandakhadyaka* (665 CE) of Brahma-gupta.

As an aside, we may note that strong belief in models has an interesting concomitant, namely the notion of *fraud*. The history of Western science is shot through with the idea of theories and models *and* of fraud. Ptolemy himself has been accused of fraud; so in more recent times have Galileo, Newton, Mendel, Millikan and a great variety of other less well-known figures. I believe the reason for this can be traced to faith in two-valued logic, namely the idea that answers to questions have to be *yes* or *no*;

models have to be *true* or *false*: there are no other options. Scientists often encounter situations where there may be discrepancies between model and observation. If the discrepancies are large the theory would of course be quickly rejected. But the crucial cases are those where the discrepancies are small but not negligible. If the scientist falls in love with the model he is tempted to ignore some of those inconvenient observations that do not agree, as many of the names mentioned above did at one time or the other, or stretch the model in bizarre ways (as Newton did with the speed of sound). If on the other hand observation is the starting point and one has no great faith in any particular physical model, which was the prevailing norm of Indian scientific thought, the question of fraud does not arise. Indian scientists, even classical ones, do not appear to have accused each other of fraud. This could not have been mere politeness, as they did make charges of ignorance or even stupidity against each other (as Brahma-gupta did on *_rya-bhat**a*, for example). We could say that fraud is the besetting sin of a model-making scientific culture.

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All these issues are connected with the subject often called *logic*. There were several schools of logic in India, but both Indian and Western scholars seem agreed that there was no truly *formal deductive logic* in India. On the other hand Indian logic seems to have been more nearly related to *inference*. An excellent collection of papers by Jonardon Ganeri (2001 *Indian Logic: A Reader*) gives valuable insight to the Indian approach to the subject. For example, the well-known authority on Indian logic, B.K. Matilal, points out In India . . . validity must be combined with truth. . . . Indian logic is not formal logic. Similarly, Schayer comes to the conclusion that The Indian syllogism is not a logical theorem but a combination of two rules of inference . To oversimplify matters somewhat, we could say that in the Indian view the only reliable axioms would themselves have to be the result of valid inference. The great Indian logician Di_n_ga (400-480 CE) declared, There are only two means of cognition (*pram_n as*), I mean inference and direct perception The Indian insistence on providing examples in any syllogistic argument has been seen by some Western scholars as superfluous and irrational, but the chief purpose of examples could well have been to keep the axioms realistic. What example would the Greeks have been able to give for their assumption that nature abhors vacuum, or that planets are embedded in crystalline spherical shells?

Some schools of logic (e.g. the Jains) went so far as to expound elaborate theories of non-unique conclusions (*an_ka-anta-v_da*) and may-be logic (*sy_d-v_da*). The Indian distrust of two-valued logic and universal axioms is related to a perceptive comment made by Wendy Doniger O Flaherty:

Many Indian texts are troubled by contradiction; their attitude in this may seem to us Platonic. . . . But they do *not* ultimately iron out the contradictions; they alter their definitions of reality in order to let the contradictions survive.

(An Indian logician would probably insist that the word *contradictions* in the above passage must be put under quotes!) There is also the related comment of Fritz Staal that what Euclid was to the Greeks, P_n\$ini (the famous Sanskrit grammarian, 5th c. BCE?)

was to the Indians. For P_n\$ini s grammar, the *As!ta-adhy_yi*, was a monumental and creative systematization of Sanskrit grammar, carried out through a series of rules and exceptions, all expressed once again in extremely compact language.

As time passes, it is not at all clear that this rather *fastidious* Indian position on logic (to use an adjective that M Hiriyanna often applies to Indian philosophy in his outstanding text) was either unjustified or inferior. The developments in physics and mathematics in the 20th century would seem to vindicate the skeptical Indian philosophical position on two-valued logic. For example Heisenberg s uncertainty principle and the wave-particle duality of quantum mechanics would not at all be philosophically disturbing to a classical Indian mind. When G del s theorem was proved in the 1930s and showed how a system of deductive logic *had* to be incomplete, one can almost hear the applause he would have received from classical Indian logicians. I must of course hasten to add that this does not for a moment mean that ancient Indians had any inkling (let alone knowledge) of quantum mechanics or of the kind of fundamental inadequacies in deductive logic that were demonstrated by G del s technically complicated proof. All that one can say is that these 20th century discoveries were philosophically acceptable, and even gratifyingly confirmatory, to a mind reared in Indian systems of thought.

From the present perspective Stephen Wolfram s proposal about *A New Kind of Science* (2002 Wolfram Media) can be seen as basically the approach of an algoriser using the power of modern computer technology. (Do not our ways of thinking about nature depend on the tools we possess?) It is known that cellular automata, embodying the very simplest computer programs running on similarly extremely simple rules, can lead to extremely complex behaviour. (To give an example of how simple the rules may be, they may prescribe how, in a row of dots, the colour of each dot is changed — say between blue and red — depending on its neighbours colours in the previous step, in an evolution of the row in discrete time. Similarly, simple collision rules between crude molecules populating a lattice — discretized space — can lead to a complex pattern of wake vortices in the flow of the lattice fluid past an obstacle.) If the simplest rules of interaction between the units of a system can lead to the complexity of nature, one begins to wonder whether nature does not operate like simple algorithms or programs. The correspondence between rules and programs, between behaviour and computation, would once again not be philosophically disturbing to Indian ways of thinking. And Gregory Chaitin (e.g. 2002 *Conversations with a Mathematician*, Springer) talks about algorithmic information and the limits of formal reasoning, about the computer as a philosophical concept, about how any given set of axioms only captures a tiny finite amount of this [infinite] information. And that s why we re in trouble . . . that is the real dilemma (:34); and he demonstrates that G del s proof was like LISP programming. The power of algorithms therefore should not be underestimated, and algorizers surely have a great deal to teach us about nature.

From this point of view what a classical Indian logician would have found most disturbing is not the science of the 20th century but that of three centuries earlier: namely the spectacular success of Newton in providing a physico-mathematical model that was algorizable and so often agreed with observation or experiment to a most remarkable degree in so many widely different situations. The power of Newtonian mechanics, both

terrestrial and celestial, was (very correctly) considered amazing even by his European contemporaries; in India it would have further been considered philosophically mysterious, puzzling and disturbing. The fact that one could go so far with just three laws of motion and the law of gravitation was something that I believe was the result of an enterprise that Indian scientists would not even have contemplated. (Interestingly, however, the *idea* of gravitation was already present in Brahma-gupta's work (7th c.), but there is no evidence of intellectual agonization over action at a distance.) We can say that Indian civilization paid its ultimate tribute to the genius of Newton when the renowned astrophysicist S. Chandrasekhar produced what can legitimately be considered a 20th century *bh_s*ya* (commentary) on the *Principia*.

To complete the picture, however, one must note that what for long had been considered the extraordinary predictive power of Newtonian mechanics has been qualified and limited by recent developments in the theory of deterministic chaos. It is now established that chaotic motion may be exhibited by special nonlinear (but strictly Newtonian) dynamical systems whose behaviour displays an exquisite sensitivity to initial conditions, and which consequently possess only a limited predictability horizon. Such systems are by no means a small or singular class, and include such classical archetypes of predictability as the pendulum, the string and even heavenly bodies. Intimations of this limited predictability (and the accompanying weak causality) of Newtonian systems were heard already around the turn of the 19th/20th centuries, but it is only in recent decades that the roots of the phenomenon have been fully understood. Sir James Lighthill, occupant of the same prestigious Cambridge chair that Isaac Newton had held three centuries earlier, went so far as to render a public apology on behalf of the scientific community of mechanicians for having misled the world at large into such a fundamentally incorrect perception of Newtonian dynamics. But the point for us here is that these recent discoveries of the 20th century once again would be philosophically gratifying to the classical Indian mind.

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On the whole the Indian approach to scientific problems seems to have been severely practical. The classical Indian scientist would have applauded what some Western scientists have recently said about models being useful lies and mathematics being like botany; if and when they turn out to be more it should legitimately be considered astonishing. But then this fastidiousness of Indian philosophy and logic have been historically very expensive for the country. Thus, while there *are* philosophical reasons why modern science did not emerge in India, these are (in the present view) deeper and not unsound, compared to the ones normally offered.

This analysis leads to an interesting aside on modern Indian science, which (during the first hundred years or so of its emergence) has very largely followed the Western style, and can claim some very significant contributions. But model-making still does not appear to come naturally to us. From this point of view it would seem that the truly exceptional scientist in India was S N Bose, whose formulation of a new statistical model for the kind of particles that have now come to be known as Bosons was very much high science in the Western spirit. (Paradoxically, though, the Bose model was really the outcome of a counting exercise — but based on what at the time were seen as

very unusual rules. Was this a fusion of Western model-making with Indian passions for counting procedures?) But the very rarity of this kind of achievement shows the enduring power of culturally determined patterns of thought. So does the work of the mathematician Srinivasa Ramanujan, who discovered brilliant new results but could rarely provide proofs for them.

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There is no time to go through other related arguments in detail, so let me summarise the position as I see it by stating a few paradoxes about Indian science.

- There have been few physico-mathematical models originating in India.
- The philosophical liberalism and pluralism of India did *not* give birth to a *modern* science here. (There is the distinct possibility that the pluralism was actually a hindrance, not a help.)
- Twentieth century physics not only did not produce philosophically disturbing thoughts in India but in fact may be said to have confirmed ancient Indian suspicions about the nature of logic and model-making.
- The Indian preference for inference over deductive logic seems ultimately to have been justified.
- The classical Indian scientific tradition is, if anything, over-pragmatic. Thus there was never any truly *pure* mathematics in India. There *was* brilliant mathematics, but this was usually inspired by astronomy, commerce or some similar application.

We must of course admire the power of a scientific approach that has been so effective in self-correction during four centuries of continuous achievement, and continues, apparently triumphantly, on its universalist quest. We must at the same time admire also a set of philosophical views that, in spite of apparently strong refutations at various times, appear to have been fundamentally sound.

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While the great mystery, therefore, is how Newtonian science got so far, using *deductive* logic on the basis of a *model* with four laws, we can also see that it was not completely successful: relativity and quantum mechanics upset the Newtonian apple-cart. It is now a common-place to say that science is only tentative; as the British physicist J J Thomson once said, *science is policy, not creed*. It may not be able — ever — to give us the *truth*, whatever that may be, but we must admit that it has been extraordinarily successful. Modern science seems to have acquired — perhaps by fortunate accident — the property that the great Buddhist philosopher N_g_rjuna called *pr_pakatva*: i.e. it delivers what it promises; it may not be Truth, but it is honest.

I believe it is this success of modern science that Einstein had in mind when he talked about how the greatest mystery about the world is that it is comprehensible (and when in fact he went so far as to suggest that the scientific revolution was a fluke). Something similar must have been at the back of Eugene Wigner's mind when he wondered at the unreasonable effectiveness of mathematics in our attempt to understand

nature. Is it possible that the great pragmatic civilizations of the East misjudged how far the quest for truth might go based on what they considered logically shaky foundations? Were our rules of inference too stringent — our pursuit of Truth so demanding — that we missed the power and insight that could be gained from what we considered a less fastidious approach to knowledge — which (again mysteriously) turns out not only to be often correct (as e.g. with the heliocentric theory), but also to lend itself to such systematic but astonishing enlargement of its scope?

I want to conclude by saying that the view one takes may well depend on the physical and intellectual *tools* one has. If the phenomenon is too complex and complicated (e.g. meteorology, biology, social science), one may be forced to resort to data analysis to infer patterns, without the aid of axioms or models; if on the other hand the phenomena are simpler (physics, chemistry, aerospace science), it seems worthwhile to try to construct suitable minimalist models or to discover the most parsimonious set of axioms; i.e. axiomatization becomes a worthwhile goal, a feasible approach. I presume modern science will go ahead pursuing both paths simultaneously. It is, in the final analysis, a question of choice of the most appropriate strategy (Thomson's policy) to tackle any given problem with the physical and intellectual tools that we happen to possess at a given point of time — as we continue with the long history of mankind's attempt to organize the reality of nature.

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Till now I have scarcely mentioned the industrial revolution. There is not enough time (or space) to consider it here at length. But we must note that, although the pioneers of this revolution like Newcomen, Watt and Stephenson were by and large not highly educated people, their attitudes to their life's work were undoubtedly influenced, to a considerable extent, by the changed intellectual climate in England that followed the scientific revolution. To the extent that this revolution did not occur in the East, the chances that an industrial revolution of the European kind would occur here were also lower.

However it must be clearly understood that, at the times we are speaking of, the East in general did not feel the need to change the prevailing global order, i.e. it was generally content with the *status quo*, whereas Europe was the economic underdog that wanted change. The reason for this was the relative prosperity of the East. The wealth of India was noted by the many foreign travellers who came here, and was sung about in English poetry. After all, India was the destination of Columbus on his voyages. Close to home, Domingo Paes wrote (ca. 1520) of the Vijayanagar Empire, 'What I saw . . . seems to me as large as Rome and very beautiful to the sight. . . . This is the best provided city in the world.' Andre Gunder Frank has made a detailed study of India in the world economy between 1400 and 1750 (1996 EPW 27 July PS-50; *Re-Orient*, Vistaar Publications). He notes that some eighty per cent of the world's GNP in the centuries before 1750 came from China, India and West Asia; indeed Europe at that time suffered from a chronic balance of payments problem. The core regions, especially of industrial production, were in China and India, which were also the primary centres of accumulation of capital in the world system. Europe was not a major economic force as far as Eastern countries were concerned. The common global economic expansion that

started around 1400 benefited Asian countries earlier and more than it did the rest of the world. Interestingly the Europeans pursued policies in the 17th and 18th centuries that were very similar to those that Asian economies adopted around 1950: namely encouragement of import substitution and then of export promotion. However the introduction of labour-saving and power-generating technologies in Europe slowly began to favour West over East. Indeed the same Indian industries that were so strong till the middle of the 18th century, namely textiles, iron and steel etc., were virtually wiped out in the first few decades of the 19th century.

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In summary, therefore, the present proposal is that, apart from the various factors that have been extensively discussed, there are two that played a major role in why the scientific and industrial revolutions did not take place in India.

First, the Indian scientific and logical tradition was weak on devising physical/mathematical models for nature, in part because there was strong philosophical skepticism about the validity of such models. Although from a fundamental point of view this skepticism was not unjustified, in the three centuries between 1600 and 1900 it was discovered in Europe that spectacularly successful models could be devised. This effort in Europe would not have been possible without the injection of Eastern inventions — major technical ones from China and brilliant mathematical ones from India, both through the creative mediation of West Asia. These inventions were married to an old Greek faith in universal principles, also served up with a new fragrance by West Asians, in a remarkably creative episode of cultural exchange, transfer and fusion. The resulting synthesis, cooperating with a technology-enabled experimental method, turned out to be unreasonably successful, and revived science in Europe after a long period of nearly 1500 years of stagnation.

Second, from an economic point of view, the East in general was strong and prosperous, the *status quo* was comfortable and there was no great internal pressure to change the global order. Although this issue has not been the major subject of analysis here, it seems to be an essential part of the overall explanation. A few more comments however may make the argument clearer. We begin by noting that India's tropical productivity in agriculture was so high that land revenue was a sufficient source of income for government, because the country was largely (although not solely) a thriving sun-and-water economy. So there was no great pressure to promote foreign trade, but in spite of this India's trade balance was in general highly favourable. Europe had to pay for Indian goods in silver because India would not accept — i.e. did not *need*— anything else; and the silver that was discovered in the Americas came in very handy for the purpose. Furthermore Indian rulers had no ambitions to subdue countries beyond their border lands, if only because our immediate neighbours on the other side had perforce to live in desert, high mountain or dense jungle. (The only attractive neighbourhood was South East Asia, where Indian influence did indeed spread in the second half of the first millennium, but (it is important to note) not through the sword.) On the other hand to West Asians India must have seemed like a subcontinental oasis, to Europeans like a subcontinental hot house. Here may lie the roots of Western dominationism, and Indian accommodationism.

It is of course not the intention to suggest here that the factors we have highlighted explain everything — the failure of India that Raja Rammohan Roy recognized and Joseph Needham so extensively articulated, as well as the roots of what an Indian might see as a European miracle. These historical events are surely very complex. But it is hoped that the present argument will lessen the mystery surrounding these issues.

From the present point of view, the interesting question is whether the turbulent encounters between East and West that have marked the last few centuries of the political, economic, social and intellectual histories of these ancient civilizations might at some time lead to anything significantly different and new. Only the future can tell.