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The Scientific Revolution Really Occurred

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The importance of the Scientific Revolution of the seventeenth century has been queried in recent years and this paper attempts to show why the notion is still essential to a proper understanding of the twin advance in scientific conceptualization and factual discovery that began in the sixteenth century and led through such figures as Galileo to the new world view of Isaac Newton. The significance of the scholastic tradition, hermeticism and alchemy is not denied, but the major breakthrough that catapulted Europe into the modern age was the outcome of new conceptual tools and a fresh outlook on nature.

Shifting philosophies, sliding interpretations

The Scientific Revolution is now so deeply entrenched in the literature that it is hard to believe that it was only given broad currency some 60 years ago, and that the first book to be entitled *The Scientific Revolution*, appeared in 1954.[1] Whereas nineteenth-century historians claimed that the great changes that catapulted Europe into the modern age were the Reformation and the Renaissance, it became common in the second half of the twentieth century to locate the major breakthrough in the twin advance of scientific conceptualization and factual discovery that began in the sixteenth century. This change of interpretation owed much to a growing concern over the role of science in modern society. When we are satisfied with current knowledge, we are seldom exercised over the way it was acquired. As long as science was considered the embodiment of rationality, its history was less an examination of actual events than a celebration of progress. This way of looking at science was given its canonical formulation, *more geometrico*, by George Sarton in *The Study of the History of Science*, a work that appeared in 1936 but was reissued in paperback as late as 1957:

> Definition: Science is systematized positive knowledge or what has been taken as such at different ages and in different places.

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> Theorem: The acquisition and systematization of positive knowledge are the only human activities which are truly cumulative and progressive.
> Corollary: The history of science is the only history that can illustrate the progress of mankind. In fact, progress has no definite and unquestionable meaning other than in the field of science.[2]

This naive view was shared by philosophers of science who claimed that science was culturally unique and sharply distinguished from other domains such as philosophy, theology or literary criticism. They pointed out that consensus was possible in science but a forlorn hope elsewhere, and they argued that this was the case because science deals with matters of fact (as opposed to armchair theories) and resolves its disputes by invoking appropriate rules of inference instead of mere rhetoric. Given this climate of opinion, it comes as no surprise that Karl Popper saw the most important task of epistemology as the demarcation between science and non science. The structure of science appeared unassailable because it was concerned with logical relations and had no truck with what Popper dismissively called the psychology of knowledge.[3]

Thomas S. Kuhn challenged the legitimacy of this rigid dichotomy between scientific justification and scientific discovery in his *Structure of Scientific Revolutions* of 1962.[4] Once the historical genesis of a theory was recognized as relevant, not only to its social acceptability but also to its content, the canons of inductive logic so laboriously elaborated by philosophers of science began to look like parlour games. Evidentiary rules and their mathematical paraphernalia fell to the ground, and real science walked away from their clutch. Logical positivists discovered to their horror that they had been armchair philosophers all along. Paul Feyerabend, having improvised himself as court jester, kept reminding them of this fact.[5] Sociologists soon stepped into the breech and invented a 'strong program' to anchor science, no longer in the ethereal realm of logic, but in the vibrating and thumping world of social and political traditions, customs and mores, however wayward or far-fetched. The pendulum now swung from high-minded logical rigour to trendy sociological determination. Once the pure light of rationality, science became a garish sign that was turned on and off by concealed societal pulsations.

What the exponents of the old and the new view had in common was a simplistic philosophy and a selective memory. If Sarton poured over the learned entries on his index-cards to find signs of progress, Feyerabend flicked through his lively notes to discover evidence of regress. Sarton exalted positivism as the key that unlocked the door to all knowledge; Feyerabend ridiculed at it as the padlock that kept skeletons from tumbling out of the closet. Neither had a genuine desire to understand what happened in the past. In their hurry to draw a moral for the present, they steamrolled their way through history and invented a mythical Galileo (Feyerabend) or a legendary Bacon (Popper). 'Example-hunters' are poor

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historians and biased philosophers. This is not to suggest that they may not be gifted, inventive or amusing; but their failure to understand yesterday's science does not qualify them to pontificate about the science of today.

A balanced view?

Not everyone countenanced Sarton's intoxication with progress, or Feyerabend's claim that science dances to the tune of 'Everything goes'. There is more to science than positivists believe, or (to paraphrase Shakespeare) there are more things in the history of science than are dreamt of by philosophers. The historian must have an eye for *all* the evidence, even when it leads him into places that were considered too murky by advocates of the linear ascent of science or too rational by those who worshiped serendipity. The Scientific Revolution is best described not by imposing a twentieth-century template on the seventeenth-century, but by attending to the actual unfolding of science against the background of the richness and the idiosyncrasies of human nature. At no time should we sever the vital link between different forms of human enquiry, or turn a real person into an abstract philosophical position. For instance, when studying figures such as Bacon or Descartes we should examine their actual scientific procedure instead of revelling in their methodological aspirations or indulging in facile equations of the type: Cartesian = rationalist or Baconian = empirical. It is this freedom from the fetters of philosophical categories that allowed the philosopher Paolo Rossi and the historian Frances Yates to offer a fresh interpretation of Francis Bacon, and to draw attention to the hitherto neglected field of the art of memory.

Rossi's brilliant book, *Francis Bacon: From Magic to Science*, which appeared in 1957, was a watershed.[6] Reading Bacon without English bifocals (empiricism in the upper part, inductivism in the lower), Rossi was able to show where Bacon came from and, hence, to explain where he thought he was going. Because he understood the language Bacon used and the intellectual tradition that he only partly rejected, Rossi made sense of many passages that had often been distorted or trivialized, but are best understood in the light of the alchemical literature with which Bacon was familiar. But having established the importance of alchemy, Rossi did not go overboard and claim that Bacon's work was the last flowering of alchemy, although others displayed less restraint and spoke of the Lord Chancellor as though he had merely updated the language of Hermes Trismegistus.

Yates broke new ground in *The Art of Memory* published in 1966.[7] She stressed that Bacon had a good knowledge of sixteenth-century treatises on memory but that he exercised his critical acumen and realized that they were in great need of improvement. Like Descartes, Bacon felt that Raymond Lull's recipes were more

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useful for ostentation than the acquisition of solid knowledge. In addition, like Descartes, he believed he could do better, but his own writings cannot be divorced from the traditional matrix, any more than the vaunted *catena scientiarum* of Descartes can be fully understood without examining the mnemotechnic and hermetic texts with which he was acquainted.

Descartes and Bacon were buoyed up by a feeling that they stood on the threshold of the laboratory that would unlock the mysteries of nature. So were many alchemists. With the advantage of hindsight, we know that their methods, even when they overlapped, were profoundly different. Nonetheless, Bacon saw himself as performing for the senses 'the office of a true priest',[8] and he prophesied that science would 'establish and extend the power, and domination of the human race over the Universe'.[9] Descartes expressed the same conviction when he wrote that the new philosophy would enable us 'to know the power and action of fire, water, air, the stars, the heavens and the other bodies in our environment … and thus make ourselves the lords and masters of nature'.[10]

Harnessing the powers of nature

What made Bacon and Descartes so confident that a technological breakthrough was just around the corner? The answer lies in part in the development of mechanical devices to increase sources of power. By 1700, the mechanical philosophy was entrenched as a method of investigation that rested on the assumption that the universe can be understood on the analogy of a machine rather than on that of an organism. The explanation of natural phenomena by matter and motion was said (by Boyle, for instance) to be the simplest, as well as the most economical, primary and comprehensive of all possible accounts of nature. With Galileo and Newton it triumphed not only in mechanics but also in cosmology and, with Descartes, in the reduction of biological phenomena to the clockwork mechanism of automata. But, we may well ask, how did natural philosophers come to expect that the correct explanation of nature would be couched, indeed must be couched, in mechanical terms? How did the Soul of the World become the Perfect Clock? By what steps did the *Machina mundi*, which meant little more than the frame or system of the world, acquire the narrow mechanical sense in which it is customarily used in the latter half of the seventeenth century? Unfortunately, there is no easy and obvious link between progress in the crafts and the rise of a new philosophical paradigm because we are dealing with a shift in expectation rather than a straightforward causal connection. The mechanization of nature was rendered possible by the mathematization of the conceptual tools used to interpret nature, but mathematics alone would not have sufficed.

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Arithmetic and geometry enhanced the understanding of machines as sources of power; they did not create them.

The positive valuation of the crafts and the growing admiration for technological innovation that we find in the fifteenth century was reinforced in the sixteenth by a number of authors on mining, metallurgy and machines. The Sienese Vannoccio Biringuccio praised openness and denounced the secret operations of alchemy as an impediment to progress. Engineers, such as Agostino Ramelli, Jacques Besson and Vittorio Zonca produced illustrated books that conveyed a precise idea of the nature and functions of the parts of a machine, and made a wide public conscious of the benefits of better machinery. Although technical advance still marched under the ensign of architecture, which included all that we now understand by the term engineering, Italian artisans were more given to reading than their ancestors and more willing to look for theoretical explanations and to expect improvement from knowledge of mathematics. Brunelleschi, who was ignorant of Latin and Greek, was befriended by the scholar Paolo del Pozzo Toscanelli, who taught him geometry. The medieval craftsman had suffered from lack of familiarity with theoretical notions and from a narrow, ingrained specialization that assumed there was only one way of doing things rightly. Renaissance artisans came to see that an analysis of the action of machines is essential to the realization of their full potential, although their ambition often outran their understanding. The engineering and alchemical writings of this period have one thing in common: they all promise more than they can deliver, and they are animated by an overpowering faith in progress. This intellectual undercurrent is revealed in the almost endless number of works that contain the word 'new' in their title.

Philosophers changed their attitude towards the crafts, partly because of technological advance, partly because of the recognition of a new purpose for natural philosophy. It is against this background that we should read the famous aphorisms at the beginning of Bacon's *Novum Organum*:

> I. Man, the minister and interpreter of nature, understands and does as much as he is able to observe of nature through reason or his senses. He neither knows nor is capable of more.
> II. Neither the unassisted hand nor the understanding left to itself is worth much. Results are obtained with the help of instruments, which are required by the understanding as well as by the hand. And just as instruments provide the hand with motion or regulate it, so they stimulate or safeguard the action of the intellect.
> III. Science and human power are one and the same.

Here the shift is clear: knowledge is power, and that power is to be used not only to contemplate nature but to modify and improve it.

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A genuine revolution

The pioneers of the Scientific Revolution owe much to those who came before them, but it would be wrong to claim that modern chemistry is simply an offshoot of alchemy or Galilean mechanics merely the outcome of medieval scholasticism. The 'newness' so loudly heralded in books and essays written at the time of the Scientific Revolution was not merely a sale's pitch or media hype. It mirrored a genuine change in the realm of knowledge, even when the change was less profound and less satisfactory than their authors believed. For instance, Galileo's *Two New Sciences* contains a novel treatment of the resistance of materials and a fresh approach to the problem of falling bodies and the motion of projectiles. The first was decidedly original although it was soon to be supplanted by a better knowledge of the cohesion of bodies. The second embodies two epoch-making discoveries in physics: (a) all bodies, regardless of their weight, fall with the same acceleration and the distance they cover is proportional to the square of the time elapsed, and (b) the path of a projectile is a parabola. These laws were destined to alter the nature of physics.

A few years later, in 1647, Pascal published a slim volume entitled *Expériences Nouvelles*, in which he described some of the experiments he had devised to produce a vacuum. These had never been performed before and they gave rise, not only to a lively debate, but to increasing experimentation on the nature and the properties of a vacuum. A few years earlier, Gaspero Berti had attached a 13 m tube to the facade of a house in Rome to test whether a siphon could raise water to a greater height than 10.5 m, the limit Galileo had assigned in his *Two New Sciences*. The incident had created a mild stir but no one mentioned it in print before 1650, three years after Pascal published his book.[11] But by 1664, Pascal's own elaborate and detailed research, posthumously published in 1663, had been superseded. Robert Boyle, commenting on 'Monsieur Pascal's small French Book' (the *Traités de l'équilibre des liqueurs et de la pesanteur de l'air* actually ran to 140 pages but this was nothing compared to Boyle's own lengthy disquisitions), found them 'ingenious' but out of date. Indeed members of the Royal Society had already witnessed better experiments, 'which could not be made out by Monsieur Pascal, and those other learned men, that wanted the advantage of such engines and instruments, as have in this been frequently made use of'.[12] A little less than a decade had elapsed between Pascal's hydrostatical experiments (1646–1651) and Boyle's *New Experiments Physico-Mechanical Touching the Spring of the Air, and its Effects* (1660). The reason for the advance that Boyle boasts about is clear from the subtitle of his book where he declares that the experiments were '*Made, for the most Part, in a New Pneumatical Engine*'.

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Pascal, like Torricelli, had produced a vacuum by inverting a tube full of mercury in an open vessel of the same liquid. The mercury in the tube had descended to a height of roughly 76 centimetres above the surface of the mercury in the vessel, leaving a vacuum at the top. Pascal was familiar with force or suction pumps, huge syringes, so to speak that were used to raise water from cisterns but he did not think of using them to pump air out of a container to produce a vacuum. This idea occurred to Otto von Guericke, the colourful mayor of Magdeburg, and was improved upon by Boyle, who arranged for introducing objects into a large glass vessel that was evacuated. This greatly enhanced the experimental conditions since it allowed for observation on a larger scale than with the Torricellian tube. Christiaan Huygens saw Boyle's engine on a visit to London in 1661, and when he returned to the Continent he had one made in Holland and encouraged the Montmor group to build one in Paris.

New vistas opened by new tools

Steven Shapin and Simon Schaffer have emphasized how the construction of instruments and their use was far from straightforward, but they have also confirmed that those who neglected instrumentation were in turn spurned by science.[13] New tools offered new means of investigation. The telescope revealed things never seen before, and issued a challenge to traditional beliefs, if not to commonsense itself. Some historians have read deep metaphysical reservations into Cesare Cremonini's reluctance to look through Galileo's spyglass, when all he complained about was his inability to focus the instrument properly. 'Looking through those lenses makes my head spin',[14] he said. A tripod to stop the telescope from wavering in his untrained hands would have done more to make him see straight than a lecture on optics that Galileo was in any case unable to supply because he never understood the geometry of visual rays. Within a short span of time, the telescopic discoveries were endorsed by those who could secure a decent telescope. In 1611, a year after the publication of the *Sidereus Nuncius*, the Jesuits of the Collegio Romano signed a formal statement confirming Galileo's findings, and they paid him the unusual honour of inviting him to a meeting at which one of them delivered an oration praising his work. Those who had derided the telescope as putting into the sky things that were not really there soon became a laughing stock themselves. Piero Dini offered to pay 10,000 scudi, ten times Galileo's annual salary, to anyone who made a telescope that would create satellites around one planet and not around others. The Great Jesuit professor, Christoph Clavius, old and ailing, did not deny that the Moon appears uneven to our eyes, although he attempted to reconcile this observation with his lifelong teaching that the surface of the moon is smooth by suggesting that the appearance of roughness was caused by unevenness in the density of the lunar material. This

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was not one of Clavius' happier guesses, but he could have said what Galileo, defending his own intransigent views, later said to Francesco Ingoli, 'It seems to me that you would like to do like the person who wanted to pull his house down because the chimney smoked'.[15]

It has often been pointed out that what the telescope revealed was not enough to prove that the Earth revolves around the Sun. This is true but the facts disclosed created a new epistemological context in which the debate over the heliocentric theory ceased to appeal exclusively to theoretical considerations about celestial harmony and mathematical elegance. The wall that separated the Earth from the celestial bodies crumbled with the sight of mountains and crevasses on the Moon, and the phases of Venus dealt a more powerful blow to geocentrism than two thousand years of speculation. Copernicus did not triumph overnight, but Ptolemy was literally disarmed by the telescope. The countless stars that Galileo had seen were witnessed by an increasing number of scientists and amateurs, and scientists like Mersenne began to take much more seriously what he termed Giordano Bruno's 'battle for the infinity of the world'. It was in this climate that Pascal wrote, 'The eternal silence of these infinite spaces fills me with dread',[16] and, 'Our dignity lies in our ability to think. Let us start from there, not from space and time that we could never fill',[17] which may be taken as the answer of the new age to John Donne's sense of alienation in a universe in which the centre is everywhere and the circumference nowhere:

> The Sun is lost and th'earth, and no man's wit
> Can well direct him where to looke for it.[18]

The telescope may not have changed beliefs overnight, but unlike the eye, telescopes could be improved and, as they became better, things were seen more clearly and described more rigorously. Lenses brought the heavens nearer, they also delved into objects closer at hand. The microscope, which was used by the Linceans in Rome to study flowers and insects, slowly acquired the medical prominence we take for granted. The infinitely small proved as much of a challenge as the infinitely large, and man's real size became increasingly problematic. The awesome character of the human predicament is captured in one of Pascal's *Pensées* where he describes the most minute of insects, the mite, which reveals under magnification a world of even more minute parts that can be divided over and over again until the last atom is reached. But why stop at the threshold of this new infinity asked Pascal. The last atom itself could conceal 'an infinity of universes, each with its firmament, its planets, its earth, in the same proportion in which we will find again the same proportion as in the first'.[19]

The telescope and the microscope gave new scope to speculation on the nature of the infinite, thereby preparing the mental space required for the new calculus and the role of infinitesimals. On a more mundane level, the thermometer and the

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barometer brought temperature and weather within the purview of quantification. Exchange of information was no longer limited by the restrictions of qualitative descriptions, and by the middle of the seventeenth century Descartes and Pascal's brother-in-law, Florin Périer, were comparing barometric observations with colleagues in Sweden. A few years later the Accademia del Cimento was designing beautiful and practical instruments that had a medical as well as a purely physical interest.

The invention of instruments to expedite computations was another hallmark of the Scientific Revolution. While in Padua, Galileo devised a general-purpose mechanical calculator or 'compass' capable of solving practical mathematical problems (multiplication, division, sighting, triangulation, calibration, etc) swiftly, simply, without previous mathematical education, and sufficiently accurately for ordinary purposes. Descartes showed how to solve two of the most famous mathematical problems of antiquity, the duplication of the cube and the trisection of an angle, with a compass of his own invention. Pascal built the first calculating machine using movable parts, and Leibniz took it a step forward. Galileo's discovery of the isochronism of the pendulum found medical application in the pulsilogium of Santorio Santorio and, with the crucial improvement introduced by Christiaan Huygens, provided the foundation of the modern clock. The seventeenth-century conquest of time and the introduction of clockwork precision and regularity in all walks and manifestation of life are now so obvious and so commonplace that we forget its momentous impact on civilization. Many of us may feel a sense of liberation to be without a watch for a short period of time, but imagine the crisis and the chaos that would instantly paralyse every country of the world if all the clocks were to stop or go on strike.

New mentalities for a new world

Not all the new facts that swam into the consciousness of the seventeenth century were uncovered with the aid of new instruments. Tycho Brahe and his contemporaries observed novae with the naked eye and recognised that they occurred where the old astronomy said they could not be, namely beyond the sphere of the Moon. New flora and fauna were brought back from voyages of discovery to other continents along with anthropological information that introduced novel elements into the quest for better forms of government. The noble savage became a political force to reckon with. This challenging new information was rapidly disseminated thanks to the invention of letter-press printing from movable type in the mid-fifteenth century. Book-printing was a boon for learning in all fields, and illustrations enabled the communication of technological innovation by means other than words alone. What could only with great difficulty be conveyed in sentences now leapt to the eyes from eloquent

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drawings in such books as those of Agricola and Ramelli that we have already mentioned. What makes Vesalius' masterpiece, *De Humani Corporis Fabrica*, so striking are the dramatic and artistic illustrations that raised structural anatomy to a new level. Simple diagrams rendered possible what would have daunted the most skilled of writers. Galileo heaved a sigh of relief when he could rely on a sketch to illustrate how a piece of machinery worked: 'I imagined a device that I can explain much better with a sketch than with words'.[20] Such possibilities were not available to an earlier age.

The new instruments, however, would have been of limited interest if they had not been coupled with deeper innovations in the realm of ideas and mentalities. In astronomy, the gradual acceptance of the idea that our apparently stationary Earth is really dashing around the Sun had a number of important and unexpected results. At the general level of philosophical discourse, it gave a new urgency to the need to distinguish between the 'subjectivity' of sense perception and the 'objectivity' of scientific language. At a more practical level, the importance of the Sun in the macrocosm led Harvey to ponder afresh the role of the heart in the microcosm. He likened the heart, the king and ruler of the circulation of the blood, to the Sun, the source and distributor of warmth and life in the universe. On the theological level, the motion of the Earth raised questions about the literal interpretation of the Bible and the relations between scientific knowledge and religious imagery. The real condemnation did not fall on Galileo in 1633, but on the theology in whose name he was put on trial, for those who knew how the heavens go started to turn their backs on those who taught them how to go to heaven.

The new science of motion, which began with Galileo's study of falling bodies and projectile motion and culminated in Newton's law of universal gravitation, changed the way the laws of physics were understood. A new relationship between 'art' and 'nature' was ushered in when 'unnatural' conditions (e.g. dropping objects in a vacuum) began to disclose the hidden truth behind 'natural' operations (e.g. how a stone falls from a tower). The related idea that we can only know what we can make gained ground in scientific discussions and was actively propagated by Marin Mersenne. What humans can know about themselves was profoundly modified by the discovery that the Earth had existed for a much longer time than had hitherto been believed. New theories about the formation of the Earth-crust initiated a slow but relentless process of re-evaluation of man's place in nature.

The Aristotelian network of ideas that was dismantled during the seventeenth century had been more than a scientific hypothesis. It defined the purpose of research and the relations between man, nature and God. Belief in the fundamental stability of existing natural structures carried with it a conviction of their wise design. When Descartes attempted to explain human physiology in mechanical terms he subverted the assumption that mankind could grasp the final causes

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or purposes for which things had been made. The design of things was sought in the original ordering of matter, and the God of History became the Maker of the Supreme Machine. Robert Boyle, who wholeheartedly accepted the Cartesian separation of mind and matter, saw the clock, and particularly the great cathedral clock of Strasbourg, as the greatest work of ingenuity contrived by man: it symbolised the highest known intelligence, and exemplified in the most elaborate detail the adaptation of means to ends. Clockwork led Boyle to celebrate the Designer, and if the Scientific Revolution turned God into a watchmaker it was not one who was blind.

Bacon and Descartes may have flirted with the arcane but they went on to marry reason. An open science is essential to an open society. Books on natural magic, alchemy and astronomy were increasingly read in a context where obscurity ceased to pass muster for depth, and outlandish claims were subjected to experimental confirmation. In the Middle Ages, philosophy had flourished in the cloisters as the handmaid of theology. In the seventeenth century, natural philosophy found a new home and a new atmosphere in scientific institutions. These played a major role in the development of the image of the man of science, who could no longer be assimilated in his outlook or his method to the magician, the astrologer, the university professor, the courtier or the humanist. The academies in Rome, Florence, London, Paris and Berlin saw the necessity of corporate investigation and international cooperation. They offered a forum where the problems of contemporary science were made known and where the methods with which they were tackled were discussed. The learned societies also played a vital role in transmitting information and encouraging the spread of science through specialized journals. If they added prestige to the role of the scientist, they also stimulated interest among a large number of amateurs and thus created a scientific public.

The goal of a unified science and the desire of achieving mastery over nature had been present in the hermetic tradition. That the same ideals should be shared by the Scientific Revolution is, of course, understandable, but it should not make us forget that the way of achieving those ends was profoundly different. Although modern science may have drawn the boundaries of rational knowledge too narrowly, it favoured logical rigour, experimental control and public debate where hermeticism merely dreamt of leaping over rationality itself. Those who deny the originality and usefulness of the Scientific Revolution would do well to pause before slipping back into the dark abyss of time.

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