What drives science forward? A brief history of science in 6½ stages.

At no other time in history has the world of knowledge changed as rapidly as today. Scientific progress accelerates at an unprecedented pace and seems to continue to accelerate without limit. It began in the early 20th century: A year after General Electric established its research laboratory in 1900 it employed eight scientists; less than thirty years later it employed 555. Bell Laboratories increased their research staff from 3,600 in 1925 to 4,200 in 1937. In Europe the Phillips Research Laboratories grew from four staff in 1914 to 415 staff in 1936.

The hectic pace of scientific research increased during the second half of the century. 100,106 chemical substances were produced industrially in 1981, more than 3,000 new chemicals have been added since then. Their existence would be unthinkable without the effort of thousands of scientists, who think of ever-new combinations for the building blocks of nature.

What causes this hectic research activity? What drives science in its quest for new insights into the laws of nature? The answer may not be straightforward, but one thing is beyond doubt: Whatever drives science forward is not necessarily what motivates scientists in their work. When a scientist is asked what drives science forward the answer is often: curiosity. But curiosity, the desire to understand for its own sake, is only one motivation among several, and not necessarily the most widespread one. Other reasons mentioned by science historians are the desire to enjoy oneself, the need to earn a living, the desire for reputation, the desire to serve humanity.[1] It is worth dwelling on these motivations a little, so that we can clearly distinguish between the forces that drive science and the forces that drive scientists.

It is true that some scientists are mainly motivated by curiosity. That curiosity should be the strongest force to drive science activity has, however, to be questioned. Scientists motivated mainly by curiosity often show very little interest in publishing their findings. But without the documentation of research results in written form science cannot move forward. Curiosity alone does not seem to achieve this. Darwin and Pavlov are prominent examples. Darwin laid the foundations to the theory of evolution, but fear to offend caused him to leave the manuscript of *Origin of Species* in a drawer for fourteen years. Only very reluctantly did he decide to make his research public when he learnt of the intentions of Alfred Russell Wallace to publish work that contained essentially the same ideas. Pavlov, recipient of the Nobel prize in physiology, was not interested in publication and was coerced by his assistants, who threatened to publish his work if he did not proceed to publication himself.

To list the desire to enjoy oneself as an independent motivation appears difficult to sustain. It is hard to see how anyone can enjoy oneself in science without having a curious mind, because without the curiosity much of the work in science is just drudgery and mind-numbing routine. In the ordinary course of science, whether one counts blood cells under a microscope or performs lengthy mathematical calculations, the enjoyment does not come from the daily routine but from the eventual finding of new facts. This is the moment described in Schiller's “Ode to Joy” – well known from its first verse in Beethoven’s Ninth Symphony – which lets Joy smile on the scientist at every new discovery: “From the truth's own fiery mirror on the searcher doth she smile.”[2]

The need to earn a living has often been the motivation for gifted members of minorities who were barred from access to everyday occupations. This explains the prominence of Jews in medicine and other research areas. During the 19th century increased demand for scientists allowed men and occasionally women from the working classes to take up a scientific career. The need to earn a living would have been a strong motivation for them as well. Today it is often argued that most scientists are not particularly well paid and could earn more in other professions, and their preference for a scientific career is proof that financial considerations are not a motivation for science. This disregards the fact that many scientists are not very good at anything except science and cannot easily enter other professions.

The desire for reputation has been a major motivation for several outstanding scientists. It is recognized by the many prizes, awards and honorary memberships of societies that can open the doors to high society. The most prominent example in history is Isaac Newton, whose scientific work revolutionized physics. Newton complained that Locke, whom he had approached for help, "would not care to visit such an unsuccessful place-hunter as himself” who “must reconcile himself to end his days in the obscurity of an academic life.” He gave science away as soon as he had gained access to the ruling class and was content to bring counterfeiters to justice as warden of the mint.

The desire to serve humanity is seen as such a noble motivation that every agrochemical, petrochemical, software or drug company claims it as one of its major driving forces in the search for profit. One has to be wary to see it quoted as motivation for industrial research. Its truth content can be better judged from the lives of individual researchers. Benjamin Franklin, inventor, scientist and diplomat, refused throughout his life to take up patents for his work, so that it could be of benefit to all. Sir Humphrey Davy, the inventor of the safety lamp for mines, refused to patent his invention because his "sole object was to serve the cause of humanity." It is possible to find examples of servants to humanity, but they are by no means the norm, and it would be adventurous to claim that they are the only ones that drive science forward.

If the various motivations of scientists cannot throw light on the question what drives science forward, a good way to approach the problem is to adopt proven scientific methods and begin with a hypothesis: Science develops where there is a need for it. We may formulate this even more stringently and say that science develops *only* where there is a need for it. Verification of the hypothesis then proceeds in the normal scientific manner: Every evidence in its support makes it more likely that the hypothesis is correct; a single fact that contravenes it will cause its downfall.

Some caution is advisable, though. It is easy to find examples of scientific research that, from the point of view of society’s needs, is absolutely useless, at least at the time when it is undertaken. But this does not invalidate the hypothesis. The question what drives science forward is not concerned with the reasons why a particular piece of research is conducted, it is concerned with the question why society promotes scientific research as one of its endeavours. To invalidate the hypothesis it is necessary to find a period in human history when science was separated from the problems of the society and developed for other reasons or no reason at all. Individual research projects with no direct connection to society's problems were always undertaken; they can invalidate the hypothesis only if they constitute the essence of the scientific effort of their time.

Adam Smith, the social philosopher and political economist of the 18th century, faced a similar problem when he wanted to understand the inner workings of industrial capitalism. He was convinced of the overall benefits of the emerging new society but wondered how the combined action of many capitalists, who all strive to maximize their individual profit, could lead to the building of schools, hospitals, houses for the poor and improved infrastructure for the country. His work "Wealth of Nations" revolves around the question how people "led by an invisible hand . . . without knowing it, without intending it, advance the interest of the society."

Smith did not find all the answers, but he distinguished clearly between the interest of the individual and the laws that determine the development of society. We can follow his example and ask how scientists, led by an invisible hand, without knowing it, without intending it, advance the interest of the society.

To find the necessary evidence in support of our hypothesis that science develops as a result of society's needs it is necessary to review the history of human society and its relationship with science. The starting point is the hunter-gatherer society. Its members shared food and other resources; private property was restricted to hunting tools and some other basic utensils. There is evidence from surviving hunter-gatherer societies that their languages do not know numbers beyond four. One, two, three, four, many – this is the number range of some indigenous tribes in Australia and in South America.

We could call such societies primitive societies, in the scientific sense that they represent an early stage in the history of human society. In everyday language the term "primitive" is laden with connotations of inferiority; but nothing could be further from the truth. It is easy to show that the mental capacity of the ordinary human being from the 21st century is very much the same as that of our hunter-gatherer ancestors and that our own conceived superiority is nothing but the result of educational instruction, during which the accumulated knowledge of millennia is handed over to us. The capacity of the human brain to grasp quantities without counting does not go beyond four or five, regardless of the type of society its owner belongs to.[3]

The need to count – to quantify groups of more than four objects – came with the advent of private property, as societies evolved from hunters to herders and individuals became owners of large numbers of animals. The first number systems invented for counting used symbols of fixed value. The only surviving such system came to us from the Roman civilization; in Roman numbers I always stands for one, V for five, X for ten, C for one hundred, regardless of where it occurs in a number.

The major use of these “absolute value” number systems was in book-keeping and administration; excavations from Mesopotamia document many trade transactions that would have been impossible without them. Their use for science is rather limited, because they do not lend themselves to algebraic calculations. (Try to multiply CCXXV with XXIX, and the problem becomes evident.) The need for science only arose with the nomadic herder society and increased with the agricultural society. Managing pasture use and tending to fields is difficult without a good understanding of the seasons, which requires a calendar.

The essence of the calendar problem is the fact that the various natural measures of time are incommensurable. The month uses the rotation of the moon around the Earth as its unit; it is a lunar phenomenon. One lunar cycle equals 29.53059 days. The year is determined by the Earth's movement around the Sun; it is a solar phenomenon with a period of 365.242199 days. For practical reasons a calendar cannot include fractions of a day, so whatever number of days is used to define a month or a year, the calendar will invariably get out of step with the real year and its seasons as time goes on. The art of calendar making consists of the way in which a lunar phenomenon (the month) is used to keep track of a solar phenomenon (the year).

To solve the calendar problem required the accurate determination of the year's length through astronomical observations over very long time spans. Documenting them required a better number system, one that allows the construction of very large numbers as well as fractions. Such number systems were invented independently in Mesopotamia by the Babylonians around 1800 BC, in China between 200 BC and 200 AD, in India before 450, and in Central America around 400 - 600. They are known as “position value” number systems, because the value of their numerals depends on their position in the number. (The numeral 2 is worth two in 302 but twenty in 325.)

The Babylonian number system used the base 60; it was very unwieldy in comparison with decimal systems in use at the time and was eventually abandoned. Another reason for its demise was the absence of a concept of zero, a necessary ingredient of any place value number system.

That a highly evolved civilization such as Babylon would struggle for centuries without a zero seems inconceivable today. It is, however, one of the strongest pieces of evidence that science only develops when there is a need for it.. Absolute value number systems do not require a zero. (The number 101 in Roman notation is simply the combination of C and I: CI.) The need for a zero only arose with the invention of the position value number system. Babylon's astronomers used the character "space" to indicate an "empty position" in a number but never grasped the concept of zero.

The future of mathematics belonged to those who mastered the concept: the Indians and the Maya. The Maya civilization developed in isolation from the Old World and was eventually destroyed during the Spanish conquest. The Indian number system was adopted by the Arabian scientists, who called India “the mine of wisdom” and credited the Indians with “excellent intellects, exalted ideas, universal maxims, rare inventions and wonderful talents.”[4] Europeans learnt about Indian numerals through Arabic manuscripts, and as a result the Indian numerals are often called Arabian numerals in the West.

The Indian number system allowed Indian mathematicians to develop the concept of logarithms around 200 BC and to tabulate harmonic functions before 600 AD. Greek mathematicians did not know a position value system, which explains their preference for geometry that can be pursued with ruler and divider. The major contribution of the Greek civilization to the development of science was that it broke the link between religion and science by establishing the new discipline of philosophy, literally "love of wisdom", for systematic attempts to understand and explain nature. This groundbreaking development requires an explanation in terms of society’s needs, or the hypothesis that science develops only where it is needed cannot be sustained.

Religion, like science, attempts to find order in nature. The difference between the two ways of understanding nature is that science develops explanations of nature through repeatable observation and verifiable experiment, while religion explains nature through unverifiable belief. Early societies had only limited means of experimentation, and their endeavour to discover the laws of nature had to rely on a range of unverifiable assumptions. As human knowledge progressed, the need for unverifiable assumptions decreased, allowing science to separate from religion.

India has always had a tradition of rational thought. Among the many Indian schools of thought were the Lokayata ("The Worldly Ones"), who rejected the idea of god and ridiculed the Brahman priests: "There is no heaven, no final liberation, nor any soul in another world, nor do the actions of the four castes produce any real effect. The Agnihotra, the three Vedas, the ascetic's three staves, and smearing one's self with ashes were made by Nature as the livelihood for those destitute of knowledge and manliness." The Lokayata were uncompromising materialists. Their ideas were probably never accepted by the majority of the population, but the great length to which Buddhist and orthodox Hindu philosophical texts go to refute them indicates that in India materialist ideas must have been influential and competed successfully with several religious schools of great wisdom and depth of thought.

The situation in Greece was different. Greek religion was not suitable as a tool to explain the natural world because it lacked the mystical depth and all-encompassing concept of other religions. Greek gods and goddesses did have more power than humans but were also prone to give in to temptation. They occasionally lusted after mortals and sometimes became mortals themselves for their misbehaviour. This peculiar trait of Greek religion has sometimes been used to invoke the character of Greek religion as the reason for the development of Greek science.[5] But if that were true, Greek philosophy should have developed much earlier than around 600 BC, when the first great Greek scholars began to teach. The explosion of rationalist thought that occurred in Ionia and Athens at the time could only be a result of changes in Greek society.

As in other civilizations of the time, land in Greece was held by feudal landlords and worked by indebted peasants or slaves. In contrast to the fertile river valleys of Mesopotamia, however, Greece is arid and mountainous, in the words of the Greek poet Hesiod "cold in winter, hot in summer, good at no time." It cannot support rich agriculture. Cities like Athens could not be fed from the surrounding land; they relied on sea trade and the export of olive oil, pottery and silver to feed their population. This created a new merchant class, which as early as 800 - 700 BC had become very wealthy. The importance of the new class is evident from the fact that between 900 and 600 BC all major Greek cities had established trading outposts along the coast of the Mediterranean and Black Seas from Spain to Italy, Lebanon to North Africa, Anatolia to the Ukraine.

The new class resented the fact that it remained excluded from power, even though its wealth often exceeded the wealth of the feudal aristocracy. This brought about the rise to power of the so-called tyrants, individuals who, being swept to power on a wave of popular uprising, installed themselves as autocratic rulers.

The period of the tyrants did not last long. Cypselus, the first documented usurper of power, established himself as tyrant of Corinth in 650 BC. Twenty years later the legislation of Dracon in Athens guaranteed equality before the law and introduced "draconian" measures to protect private property from usurpers. A new constitution drawn up by Solon in 594 BC abolished all peasant debt, guaranteed peasant ownership of land and established four classes of citizens according to income. To safeguard the new social order known as "democracy" (literally "rule by the people") mercenary armies were replaced by citizen militias, and government was established through the assembly of citizens.

The Greek religion was particularly appropriate for the new social order, but it was not the driving force of social change. The idea of an all-mighty god in undisputed control of the universe is the religious equivalent of the autocratic ruler. A society that allows every free man to stand up in front of his fellow men and convince them through good argument has to allow its gods the same privileges; it cannot imagine heaven more restrictive than earth.

It is clear that a change of society as fundamental as the transition from feudal to democratic rule would bring change in all areas of life. Science was no exception and had really only one restriction: The new order was open for all free men, not for women, and not for slaves. But from the free men were sure to rise those who would teach others reason and good argument. All they had to do was impress the democratic assembly with a well thought-out speech and good presentation. This required training. Speaking to an assembly of a few thousand men without a public address system was as much a physical effort as an intellectual challenge, and the art of rhetoric was highly regarded. Philosophers who could speak well and teach others to do the same appeared shortly after 600 BC. The first Academy to train the free men of Athens to speak in public and to teach them what to talk about was founded by Plato in 387 BC, followed by Aristotle's Lyceum in 355 BC.

Support for the hypothesis that science develops in response to society's needs comes also from the activities of the philosopher-scientists themselves. Many saw their role as assistants to the new order and were active in politics. Plato established his Academy for the declared purpose to train future politicians and took an active role in consultancies of various kinds. Members of his Academy were involved in the formulation of laws for several city-states.

When the Romans inherited the achievements of Greek science and began to follow its mode of thought, the philosopher and politician Seneca expressed the difference between the old interpretation of natural phenomena that relied on supernatural intervention and the new rational thought clearly when he compared the Tuscan tribe with the Roman tribe: "There are differences of interpretation between our countrymen and the Tuscans, who possess consummate skill in the explanation of the meaning of lightning. While we think that because clouds collide therefore lightning is emitted, they hold that clouds collide in order that lightning may be emitted. They refer everything to the will of God; therefore they are strong in their conviction that lightning does not give an indication of the future because it has occurred, but it occurs because it is meant to give this indication."[6]

But the Romans were more interested in the building of roads, fortifications and water supplies for their empire. They could do without philosophy and left the practicing of science to the Greek intelligentsia in Alexandria, their colonial outpost in Egypt. The fate of Greek science was foreshadowed by the burning to the ground of the remains of Alexandria's famous library by Christian fanatics in 391 and sealed in 415 when the director of its museum was murdered by monks.

For the next 400 years the leading science nations were found in the east. While European science was in decline, India consolidated its lead in mathematics, optics and other areas of science. In China the relative worldliness of Chinese religion combined with the stability of China's system of government to provide support for science as an imperial responsibility, at least to the extent that political upheaval did not disrupt ongoing work to maintain the country's infrastructure. This led not only to the longest existing observational records of modern astronomy but also to conditions that were particularly favourable for applied science and inventions including the compass, paper, and printing with movable type 400 years before Gutenberg invented the technique again in Europe.

The next significant development in the history of science occurred with the rise of Islam in the 8th century. Culturally and intellectually the rulers of the new Arab empires were tribes people from the desert. They were skilled and fearless horseback fighters, who could overrun vast regions and keep the defeated people enslaved or bound to the payment of tribute, but they had no tradition of scientific achievement. They did not, in this aspect, differ much from the Mongols, who overran an entire continent in the 14th century. There is, however, one important difference between the Arab caliphates and sultanates and the Mongol empire. The Arab rulers had the new religion of Islam to guide their empire building activities. They knew their obligations to look after the poor and after the sick and sought the assistance of science in the organization of their empire. The Mongols did not have that ethical ideal; their arrival usually meant senseless death and large-scale destruction.

Given their tribal background, the Muslim rulers required the assistance of the conquered people to build their new empires. They could impose their language – Iraq, Syria, Palestine, Egypt and all of northern Africa adopted the Arabic language, and the term "Arabic" has a much wider meaning today than in Muhammad's time – but on their own the clans and tribes of Arabia had neither the numbers nor the level of civilization required to take over and run such advanced societies as Persia or India.

It seems that the need to use existing intellectual resources was one of the reasons why the various religions they encountered were not all treated in the same way. Jews and Christians had to pay the *jizyah*, a poll tax levied on all members of non-Islamic communities, but they could maintain religious autonomy, and their synagogues and churches were protected. In contrast, members of other religions ("pagans") were confronted with the choice of conversion to Islam or execution. The official argument for the special treatment of Christians and Jews was that they are "people of the Book" (*ahl al-kitab*) who believe in the same God as Muslims and have sacred scriptures. A major motivation for leniency towards their beliefs appears to be that the intellectual elite of the existing civilizations, which was needed for the administration of the new empires, came from these groups. Support for this analysis comes from the fact that the followers of Zoroastrianism and Hinduism, who could hardly be classified as believers in Allah, were also assigned the status of “people of the Book” as soon as the Islamic empires expanded into the civilizations of Persia and India.

The early development of Arabic science was determined by the necessities of building the Islamic state. The Umayyads, the first dynasty of caliphs, introduced the Chinese technology of paper-making and supplied the madrasahs with writing paper produced in their capital Damascus. Al-Mansur, second caliph of the Abbasids (the second caliph dynasty) established a state-run paper mill in Baghdad to have translations of scientific works made from all civilizations. The translation turned into a major effort. To begin with, the languages of the educated elite of the Middle East were Pahlavi (the language of the Persian empire now governed by Arabs) and Syriac (the language adopted by the Christian church). Persian, Christian or Jewish scholars who knew Greek or Sanskrit (the language of Indian science) did not speak Arabic. An additional problem was that Arabic, the language of desert tribes and merchants, lacked the words for many scientific terms, which had to be invented and explained in simple words for the Arab reader. As a result, translation was usually achieved in two stages. A Christian, Persian or Jewish scholar translated the text from Greek or Sanskrit into Syriac, and an Arab, who was not necessarily educated in the sciences, completed the translation into Arabic.

The process required some 150 years before Arabic science was ready to build on the inherited knowledge and make its own original contributions. This phase began with the decision of al-Ma'mun, caliph from 813 to 833, to establish a "House of Wisdom" (*Bayt al-hilkma*), the largest such institution in the Mediterranean region since the Museum in Alexandria, and bring together a team of scientists to verify Ptolemy's data of his astronomical work *Almagest*. The House of Wisdom produced the first astronomical tables made in an Arabic empire that surpassed all existing tables in accuracy. The project was helped without doubt by another great achievement of Arabic science, the combination of Greek geometry with Indian arithmetic. This was the work of the mathematician al-Khwarizmi, whose name lives on in the word "algorithm." The introduction to his masterpiece *Kitab al-jabr wa l-muqabala* (literally "The Book of Reduction and Comparison") provides another example how science develops in response to society's needs:

"The imam and emir of the believers, al-Ma'mun, encouraged me to write a concise work on the calculations *al-jabr* and *al-muqabala*, confined to a pleasant and interesting art of calculation, which people constantly have need of for their inheritances, their wills, their judgements and their transactions, and in all the things they have to do together, notably, the measurement of land, the digging of canals, geometry and other things of that kind."[7]

By the 15th century the Muslim empires had begun their intellectual decline, but the rational attitude of Muslim science had already infected Europe. Gerbert of Aurillac had discovered Arabic works and Arabic translations of Greek texts in Spain's monasteries in the 10th century and prepared Latin translations. 200 years later Adelard of Bath had continued this effort. Europe had still been in intellectual darkness at the time, and Adelard had despaired about the state of English society; his work *Quaestiones naturales* describes how on his return from studies of Arabic texts in Sicily he gave in to the pleas of a nephew, who "urged me to publish something fresh in the way of Arabian learning. ... I took in hand the treatise which follows: of its profitableness to its readers I am assured, but am doubtful whether it will give them pleasure. The present generation has this ingrained weakness, that it thinks that nothing discovered by the moderns is worthy to be received."

Another 300 years later Europe was ready to rediscover Greco-Roman philosophy during the Renaissance. The focus of the new spirit of independent thinking and openness to new ideas was Florence, the centre of world trade and world finance and home to the Peruzzi and Medici banking houses. There was barely a royal house that was not deeply in debt with them, and the power of bankers began to rival the power of kings. This brought a new element into society. While the feudal aristocracy spent money on palaces and wars, banking houses operated to make a profit. Their merchant capitalism did not justify itself through the feudal doctrine of God-given rule but was based on the right of individuals from other classes of society to try their luck in the world. The new spirit of free enterprise allowed Europe's philosopher-scientists to embrace Arabian texts and through them Greek and Indian science.

The Church, which had provided the ideological underpinning for feudal rule, had no choice but to adapt to the new circumstances. It declared itself the logical successor of Greek philosophy. In 1510 Pope Julius II commissioned Raphael to decorate his apartment in the Vatican with two giant frescoes; one wall was to show the classical philosophers, while the wall on the opposite side of the room was to depict God, the prophets, apostles and representatives of the church. Raphael's "School of Athens" turned into one of his masterpieces; it depicts Plato and Aristotle in animated discussion, surrounded by famous Greek, Persian and Arab philosopher-scientists.

From the point of view of science the Renaissance was not a period of innovation and progress, as it undoubtedly was in regard to society in general; it was a period of recovery of lost knowledge and assimilation of foreign knowledge. It is true that the roots for innovative European science were already laid in the Renaissance; in 1510 - 1511, while Raphael painted the School of Athens, Copernicus summarized his ideas about the movement of the Earth around the Sun in "A commentary on the Theories of the Motions of Heavenly Objects from their Arrangements", a work that opposed the teaching of Ptolemy that the Sun and all planets revolve around the Earth as the centre of the universe. He refused to have his work published, for good reason: The Church had managed to overcome its hostility to the Greek classics and decided to present itself as their legitimate heir; but this was definitely not the time to question the classics' teachings.

What followed is well known. Kepler published his "Epitome of Copernican Astronomy" in 1618 – 1621. Galilei, who had been in correspondence with Kepler since 1597, published his "Dialogue on the Two Main World Systems, Ptolemaic and Copernican" in 1632, was forced to recant and placed under lifelong house arrest. The Catholic church had decided to oppose the new scientific findings. In 1616 it had declared the Copernican theory "false and erroneous" and had made any alternative teaching to Ptolemy's theory punishable by death. But science progressed despite these threats. It did so in response to the needs of society, of which there were two: improvement of the Julian calendar, and determination of geographical longitude at sea. It is an irony of history that the church became an unwilling assistant in the process.

The Julian calendar had been developed by the Greek astronomer Sosigenes of Alexandria, who had been commissioned by the Roman emperor Julius Caesar to clean up the hopelessly muddled situation of Rome's calendar system. Sosigenes had recommended the adoption of the Egyptian year length of 365.25, slightly longer than the true length of the year. As a result the calendar slipped again against the seasons as time went on. By the 16th century the error had reached 10 days and affected the determination of Christian holidays such as Easter. Discussions about an improved calendar were held in the Catholic Church for quite some time. Finally, in 1545 a church council authorized Pope Paul III to take action.

The task to determine the length of the year with the necessary accuracy was a challenge for science. By promoting new and better astronomical observations, the church created a major problem for itself: The more observations became available, the more difficult it became to reconcile Ptolemy's theory of the solar system with the observations. By the time Pope Gregory XIII could finally introduce the reformed calendar in 1582 the damage had already been done; the new Gregorian calendar was more accurate, but the Ptolemaic system had become indefensible.

The second need of society resulted from Europe's move into colonial conquest, which required the crossing of vast expanses of open ocean. Safe navigation requires that a ship's master knows the position of his vessel. The geographical latitude (the ship's distance from the equator) could be obtained by observing the highest position of the Sun during the day. Determination of geographical longitude (the east-west distance from a reference longitude, which today runs through Greenwich in England) requires the measurement of the difference between the time when the sun rises at the ship and the time when it rises at the reference longitude. Existing clocks did not keep time accurately enough to be of any use for this, and science struggled for a long time to find a solution. Galilei hoped to develop a celestial clock and spent endless nights to obtain observations of Jupiter's moons with the highest possible accuracy for that purpose. He even designed an observer's chair for use on ships. The mathematician, astronomer and physicist Christian Huygens had the same aim when he experimented with the pendulum, hoping to be able to use it for accurate timekeeping. His idea pointed in the right direction, but clocks on ships travel through many climate zones, and Huygens did never achieve complete temperature compensation; his pendulum expanded in the tropics, which made it slow down, and got shorter in the cold, which made it speed up. Robert Hooke and Gottfried Leibnitz also worked on the longitude problem, both without success. The problem was eventually solved in 1714 not by a scientist but by a craftsman, the carpenter and self-taught watchmaker John Harrison who built the first chronometer, a clock that keeps accurate time under all conditions at sea.

Although the efforts of scientists to solve the longitude problem were not met with success, they demonstrate that science driven by society's needs can and does produce unintended useful results. Galilei's intense observations of Jupiter hastened the collapse of the Ptolemaic view of the universe, Huygens' work led to great improvements in the measurement of time.

Capitalism, the social order of the future, had infiltrated European feudalism already during the 15th and 16th centuries in the form of merchant capitalism. *The Reformatio Sigismundi*, an anonymous tract that circulated in Germany during the 15th century, gives a graphic account of its effects: " It is to be also known that something worse in the cities arose and also in the country: Everyone wants to engage in trade, to more than he is entitled. One is a wine man and keeps salt on offer and cloth; one is a tailor and a cloth man; one is a shoemaker and tans as well; just look at all the trades! Whoever can manage a trade operates it; one sees in some cities that four or five operate so much trade that should be sufficient for twenty. ... There also appeared big companies, which band together and carry on trade; ... they engage in various tricks and sham that becomes the cities and countries badly. One must not allow that such companies are found anywhere, be it by nobles or burghers; and where they are found, they or their agents, we order at the empire's pleasure and give everyone permission to subjugate them and rob them with full permission, to take from them what is theirs, as much as one can get hold of, until they are destroyed; one must watch out for them, for they harm all countries. Whoever wants to carry on his trade shall take it up and let go all others; that way everyone can have a living. "

These were, of course, futile recommendations. The rise of capitalism as the economically superior form of society could not be halted. The fall of the feudal autocratic regimes began in 1581, when Holland freed itself from Spanish rule and established a republic. It took a decisive turn with the English Civil Wars of 1642 - 1646 and 1648 – 1650. The Habeas Corpus Act of 1679 and the Bill of Rights of 1689 ended feudal power over the citizen and allowed scientists to contradict the Greek view of the world without fear of persecution or death.

In the 17th and 18th centuries merchant capitalism developed into industrial capitalism, based on inventions of machines that eventually lead to the industrial revolution. Industrial machinery required a totally new understanding of nature. According to Ptolemy, motion is a property of matter: It is in the nature of objects close to the centre of the universe to fall to the centre, while objects at the fringes of the universe, by their very nature, move on circles. Newton established the new fundamentals of physics when he published his laws in 1679, the year of the Habeas Corpus Act. His laws declared gravity as the new universal property of all matter; motion was now understood as the result of interacting forces.

One might be tempted to argue that the invention of the "Spinning Jenny" in 1764 or James Watt's improvements on the steam engine in 1765, events often used to mark the beginning of the industrial revolution, occurred 85 years after Newton formulated his laws and cannot reasonably be invoked as motivation for work done in 1679. But the process of industrialization had started well before Newcomen invented the steam engine in 1712. Let us also remind ourselves that the motivations of individuals do not necessarily coincide with the direction of science. To support the hypothesis that in Newton's time, too, science developed in response to need we have to show that the general thrust of science was steered by the problems of society. There is plenty of evidence that this was the case.

Science changed its character profoundly during the 17th century. For millennia, from the early civilizations of India and Mesopotamia to the feudal empires of Europe, science had been a privilege of the ruling class, who could establish and maintain the monasteries and academies where a few selected members from its ranks could learn to read and write. The vast potential of scientific talent available in the general population had gone mostly unused. Even great minds were held back during feudalism, as was witnessed eloquently by da Vinci, who wrote: "I have many and most admirable plans and devices; but they could only be put to work by princes, because it is they who are able to carry on war, build and defend fortresses, and for their regal sport make most splendid expenditure, and not I or any private gentleman."

The priest-scientists in the monasteries and philosopher-scientists in the academies mostly looked down on artisans and showed contempt for experiments, which they considered business fit for tradesmen's workshops. The new attitude of science after feudalism was expressed by the English chemist Robert Boyle (1627 - 1691), who said that "many phenomena in trades are, also, some of the most noble and useful parts of natural history; for they show us nature in motion, and that too when turn'd out of her course by human power; which is the most instructive state wherein we can behold her. And, as the observations hereof tend, directly, to practice, so may they also afford much light to several theories."

To meet the demand for the understanding of forces, scientists had no choice but to turn to experiments. Where freedom of thought had been established, scientists worked on the new dynamics of motion (Huygens in Holland, Hooke and Newton in England). Where the Catholic Church still made such science punishable by death, they experimented with barometers and vacuum tubes instead (Torricelli in Italy, Pascal in France). In all countries science had left the realm of philosophy and established itself as an activity based on scientifically guided experiments. Discussions in the newly established science academies often revolved around practical problems. A study of four years of meetings at the Royal Society found that 59% of the topics were "(potentially) useful in one way or other"; only 49% could be classified as "pure science."[8] On the continent the link between science and its immediate practical use was probably even stronger, since scientists were state employees and could be ordered to apply their skills to military or other problems at any time. An analysis of the work and lives of 630 scientists of the period concluded that only 148 of them, or 23.5%, never concerned themselves with technological applications.[9]

That science was increasingly driven by the needs of capitalism became evident during and after the French Revolution. 89 spinning machines existed in France when the revolution began in 1789; sixteen years later there were 3300.[10] The revolutionary government took steps to put science directly at the service of the bourgeoisie, not in the sense that it required scientists to apply their knowledge to the day-to-day problems of factories (although such applications did without doubt occur) but for the creation of conditions that allowed capitalism to expand and prosper.

One of the more urgent tasks for the expanding trade that resulted from the rapid development of industrial production was the standardization of measures. It was simply not possible to mass produce even such simple goods as cloth, shoes or nails if every little dukedom had its own units. There had to be an end to Zoll, furlongs, Ellen, yards and whatever other units of length there were across Europe. In 1790 the republic requested the French Academy of Sciences to "deduce an invariable standard for all the measures and all the weights." The result was the International System of Units that introduced the metre, second and kilogram as base units for length, time and mass.

French scientists responded to the need of society in the same way as the Greek science-philosophers, who offered their ideas for the establishment of the new democracies, and the scientists of the House of Wisdom under al-Ma'mun. Many served in government positions or took government jobs. Jean Sylvain Bailly, the first President of the Constituent Assembly and the first Mayor of Paris, was an astronomer and historian of science; Marie-Jean Nicolas Condorcet, the mathematician and president of the Academy of Sciences, was a member of the Legislative Assembly; the mathematician, astronomer and physicist Pierre-Simon de Laplace was a Senator and for a brief period Minister of the Interior under Napoleon; the mathematician Gaspard Monge became Minister of the Navy; the physicist Pierre-François Arago and the mathematician Joseph-Louis Lagrange were Senators; Antoine-Laurent Lavoisier, the founder of modern chemistry, supported the revolution through participation in various committees; and the list goes on.[11] Which government of today can show such involvement of science in the running of the affairs of the state?

If it is correct that science since the French Revolution is driven by the needs of capitalism, it follows that science is driven to improve the general conditions for profitable business. One result of the support of profitable business from science was the discovery of evolution. Between 1700 and 1850 the leading European powers financed costly expeditions to all corners of the globe to search for profitable colonial resources. A note from the Comte de Pontchartrain to the Secretary of the French Academy of Science, dated 16 January 1700, spelled out the purpose of one such undertaking: "I have informed the King, Sir, of the proposal that has been made to send M. de Tournefort, a botanist of the Academy of Science, to Greece, Constantinople, Arabia, Egypt and the Barbary Coast, there to investigate the plants and the metals and minerals, to learn about the illnesses of these countries and the remedies which are used there, and about everything regarding medicine and natural history; His Majesty has strongly approved his design, desires that it be carried out, and has no doubt that it will be of great usefulness in the improvement of medicine and the advancement of the sciences."[12]

To make best use of the specimens returned from these voyages royal pleasure gardens were turned into scientific institutions. The Royal Botanical Gardens in Kew near London, the botanical garden of the Musée National d'Histoire Naturelle in Paris and the Imperial Botanical Garden in Saint Petersburg all received new large greenhouses to accommodate and propagate tropical plants.

The discovery of thousands of new plant species called for a reorganization of biology. The Swedish botanist and explorer Carolus Linnaeus had taken the first step and developed a taxonomic system of plants and animals. The French philosopher Rousseau wrote in 1774: "I ask every intelligent reader how it is possible to pursue the study of plants, but reject the study of nomenclature. It is as if one wished to become learned in a language without wanting to learn the words. ... It is a question of knowing whether ... the knowledge gained by all the scientists who have devoted their money, their lives and their attention to the immense, costly, difficult and dangerous voyages, are useless to their successors. ... To accept the study of botany but to reject that of nomenclature is therefore to fall into the most absurd contradiction."[12] The theory of evolution was the logical next step in understanding the overwhelming variety of life that had come to light through the reports of explorers.

The 19th century saw the rapid growth of the universities, the 20th century the creation of state research organizations. The role of both institutions is often described as the promotion of "pure research", in contrast to the "applied research" undertaken by the ballooning research departments of industry. In reality it was a division of labour in which the industry laboratories followed the narrow interests of companies, which they protected by patenting their research results, while the universities and state research organizations performed research for the common good of the national capital. Today the distinction between pure and applied research is more blurred than ever; there is no difference between pharmaceutical chemistry projects in chemistry departments of universities and in laboratories of the pharma industry or between nanotechnology projects in physics departments and in the microtechnology industry. As governments require universities to generate larger and larger parts of their budget through industry funding, universities are keen to patent their research findings, and many of their research projects are directly designed to fulfil the demands of industry sponsors.[13]

A remarkable departure from this pattern occurred early in the 20th century. Russia's Peter the Great had made a valiant attempt to match Europe's industrial development in his own country; but his efforts were stifled by his successors, and Russia had fallen back into feudalism for another 300 years. The end of Russian feudalism came with the October Revolution of 1917, which made science a central instrument for the construction of a modern Russia. The Academy of Sciences, founded by Peter the Great in 1724 and opened by his widow Catherine I a year later, had been controlled by aristocratic members of the court; it was reorganized into a democratic organization with a president elected by its members and grew at a rapid rate.

But the Soviet government did not promote science as a means to create optimal conditions for profit-seeking companies. Through central planning based on the requirements of a society in transition it turned the USSR from an agriculture-based society into a modern industrialized country in little more than 20 years. Such rapid development was impossible without the help of science. Soviet government support for science allowed outstanding researchers to flourish. The physiologist and surgeon Pavlov, who had received the Nobel prize in physiology in 1904 for his work on conditioned reflexes, was given unlimited scope for his research and transformed the physiological institutions headed by him into world centres of scientific knowledge. The educator and psychologist Vygotskij, whose groundbreaking education psychology has reached the West only recently and is beginning to have great impact, was provided with funds to establish an institute for the education of disabled children. The plant geneticist Vavilov received funding to organize the first plant collections from many parts of the world in an effort to improve agriculture in Siberia. As a result the USSR became the world leader in species collection and conservation; Vavilov's expeditions provided samples of 50,000 varieties of wild plants and 31,000 grain specimens for Russia's seed banks.

The involvement of scientists and the standing of science during the early years of the Soviet Union rivalled the appreciation of science during the French Revolution. Even Pavlov, who was never a communist and could level the most biting criticism at the

Soviet government, admitted that "formerly science was divorced from life and alienated from the people, but now ... the whole nation respects and appreciates science."

An argument that is often used to justify the use of scientific research in support of capitalist society is that such science provides solutions to the world's problems. In the young Soviet Union, in which science was not performed to support a profit-driven industry but to build an economy that could survive a foreseeable attack by Nazi Germany, this idea that science can cure all problems became so strong that it grew into a form of religious belief. It led Pavlov to enthuse: "I am deeply and irrevocably convinced that along this path will be found the final triumph of the human mind over its uttermost and supreme problem - the knowledge of the mechanism and laws of human nature. Only thus may come a full, true and permanent happiness. Let the mind rise from victory to victory over surrounding nature, let it conquer for human life and activity not only the surface of the earth but all that lies between the depth of the seas and the outer limits of the atmosphere, let it command for its service prodigious energy to flow from one part of the universe to the other, let it annihilate space for the transference of its thoughts - yet the same human creature, led by dark powers to wars and revolutions and their horrors, produces for itself incalculable material losses and inexpressible pain and reverts to bestial conditions. Only science, exact science about human nature itself, and the most sincere approach to it by the aid of the omnipotent scientific method, will deliver man from his present gloom, and will purge him from his contemporary shame in the sphere of interhuman relations."[14]

The reality is of course that science, although driven by the needs of society, is oblivious to its uses. Whether the insights of nuclear science are used to fight cancer or to produce bombs is not a scientific decision but a political choice. The omnipotent scientific method can only deliver man from his gloom if there is a political will, and if the driving force of society is profit this will is often lacking. The demise of the revolutionary Soviet model and persecution of scientific investigation under Stalin – Vygotskij's work was declared unscientific in 1936 and his writings remained banned for 30 years; Vavilov was attacked by a party careerist as "reactionary, bourgeois, idealist and formalist" and died in prison from malnutrition – ended a historical experiment, and today all science serves again the capitalist agenda.

After this review of the history of human society and its relationship with science it is appropriate to ask whether a situation can develop when science is no longer driven by the search for profit. There are indications that the 21st century generates new needs of society that may have to replace the race for profit as the driver of science. These new needs arise from the threat to the biosphere from environmental destruction.

A recent report of the European Commission states that of the more than 100,400 chemical substances that are produced industrially today, only 27 have undergone complete risk assessment. In the last 15 years public authorities responsible for environmental risk assessment have only been able to identify 141 high-volume chemicals for risk assessment and possible recommendations for risk reduction.[15] It is a safe assumption that these numbers reflect the ratio of scientists employed by industry to find new chemicals against scientists employed by governments to assess the associated risks.

In February 2001 a White Paper on a "Strategy for a future Chemicals Policy" issued by the European Commission suggested the introduction of legislation that represents a shift from science in the service of profit towards science in the service of a better society. The legislation, known under the acronym REACH (Registration, Evaluation and Authorisation of Chemicals), aims at a comprehensive system under which every industrially produced chemical has to be shown to be environmentally harmless before it can be marketed. The role of government authorities will then be reduced to registration of the products and verification of the data provided by industry. The proposed legislation has undergone several years of consultation, during which the chemical industry not surprisingly complained about the additional cost of the required proof of environmental compatibility. The original REACH draft has experienced many changes as a result, and it remains to be seen how much of the initial concept will remain in the final legislation. The fact remains that REACH is the first attempt to turn the focus of science from unlimited innovation in support of profitable goods to protection of our planet's health.

The development of science and society is a series of rapid ascents separated by long stretches of level road. This brief survey looked at six stages and the reasons that caused them: the invention of numbers to count property; the invention of the position value number system to deal with the calendar problem; the separation of science from religion and the establishment of philosophy to serve the needs of the Greek democracies; the amalgamation of Greek and Indian science for the benefit of the rising Muslim empires; the separation of science from philosophy and the move to experimental science required by industrial capitalism; the prominent role of science in the Soviet experiment of a socialist society. At every stage in the road it was seen that science was driven by society's needs.

Could it be that we are coming to the end of a long level stretch of road and approaching a new ascent, when the hunt for profit as the reason for scientific investigation will be replaced by the need to maintain a healthy planet? It would require a shift from an emphasis on innovation towards an emphasis on environmental impact control. Instead of employing thousands of industry scientists for the invention of new products and a handful of government scientists to assess their impact on the environment, the new paradigm would require a handful of scientists to look for new products and an army of scientists to make sure that the environment is kept healthy. The European REACH initiative points in that direction. It may well represent the first step on the climb of science to a new level.

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[1] Crowther, J. C. (1967) The Social Relations of Science, revised edition. The Cresset Press, London.

[2] “Aus der Wahrheit Feuerspiegel lächelt sie den Forscher an.”

[3] I demonstrated this in a classroom environment by showing the class groups of objects for a fraction of a second and letting the students write down how many objects they

thought they had seen. The success rate drops quickly if more than five objects are shown, independent of the students' age, whether they are 17 years old or 70.

[4] quoted from *Tabaqat al-Umam* ("Categories of Nations") by 11th century historian and scholar Said al-Andalusi, who lived in Córdoba.

[5] see for example Williams, L. P. (1995) Science, the history of, in *Encyclopædia Britannica* 15th ed.

[6] Seneca, *Naturalium Quaestionum* (II, 32,2), quoted from Bloch, R. (1957) Etruscan science. In R. Taton (ed.) La Science Antique et Médiévale, Presses Universitaires de France; English translation by A. J. Pomerans (1967) "Ancient and Medieval Science", Thames and Hudson, London. 551 pp., p. 266 (Volume 1 of "A General History of the Sciences")

[7] Benoît, P. and F. Micheau (1995) The Arab Intermediary. In: M. Serres (editor): A History of Scientific Thought, Elements of a History of Science. Blackwell, Oxford, 191 - 221. (Translation of Éléments d'Histoire des Sciences, Bordas, Paris, 1989)

[8] Hall, A. R. (1983) The Revolution in Science 1500 - 1750. Longman, London.

[9] Westfall, R. S. (1993) Science and technology during the scientific revolution: an empirical approach. In J. V. Field and F. A. J. L. James (eds.): Renaissance and Revolution; humanists, scholars, craftsmen and natural philosophers in early modern Europe. Cambridge University Press, Cambridge.

[10] Anderle et al. (1966) Weltgeschichte in Daten. VEB Deutscher Verlag der Wissenschaften, Berlin.

[11] Serres, M. (1995) Paris 1800. In: M. Serres (editor): A History of Scientific Thought, Elements of a History of Science. Blackwell, Oxford, 191 - 221. (Translation of Éléments d'Histoire des Sciences, Bordas, Paris, 1989)

[12] Drouin, J.-M. (1995) Lavoisier: From Linnaeus to Darwin: Naturalists and Travellers. In: M. Serres (editor): A History of Scientific Thought, Elements of a History of Science. Blackwell, Oxford, 401 - 421. (Translation of Éléments d'Histoire des Sciences, Bordas, Paris, 1989)

[13] A possible distinction between pure and applied research is based on the different motivations of individual capital and the capitalist state. Individual capital always aims at profit maximization and is assisted in this by applied research; pure research aims at the "public good".

[14] Pavlov, I. P. (1928) Lectures on Conditioned Reflexes, Twenty-five Years of Objective Study of the Higher Nervous Activity (Behaviour) of Animals; volume one translated and edited by W. H. Gantt. Lawrence &Wishart, London.

[15] European Commission (2004) REACH in brief. Available on the website of the Commission.