On the frontiers of science

Unesco Volume 27, No. 1, January–March 1977

impact of science on society

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impact of science on society

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An invitation to readers

Reasoned letters which comment, pro or con, on any of the articles printed in **impact** or which present the writer's view on any subject discussed in **impact** are welcomed. They should be addressed to the Editor, **impact of science on society**, Unesco, 7 Place de Fontenoy, 75700 Paris (France).
Requests for permission to reproduce articles published in **impact** should be addressed to the Editor.

Dedication

This issue of **impact of science on society** is dedicated, with warmth and gratitude, to the many translators who make possible the conversion of manuscripts written in many languages to the five languages used in this publication : Arabic, English, French, Portuguese and Spanish. Because the translators work in teams, in order to check and cross-check the accuracy of their work, they must remain in anonymity. The present issue of the journal has presented them with an especially challenging travail, to which they have responded with their usual industry, patience and thoroughness. The journal could not exist without them.

impact

Reminder to readers

impact of science on society is published regularly in Spanish by the Oficina de Educación Iberoamericana, Ciudad Universitaria, Madrid 3 (Spain).

The journal is also published in Arabic by the Unesco Publications Centre in Cairo, No. 1 Talaat Harb Street, Tahrir Square, Cairo (Egypt).

The magazine is also available now in Portuguese as **impacto da ciência na sociedade.**

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Comment

Some observations follow on the publication of this issue on science's new frontiers and on the readership survey made in 1976.

This issue of your journal, planned and prepared as all others fifteen months in advance, is different. Different, because its authors talk about science with little reference to its implications for society. We have long believed that many of **impact's**, readers were being cheated in the presentation of many of the themes treated over the years, being deprived of discussion on science at the expense of detailed examination of the social dynamics of science and technology and the socio-cultural influence these have on the world's civilizations. The results of our readership survey of last year seem to substantiate this apprehension (see the analysis of readers' responses to the questionnaire distributed with Vol. 26, No. 1/2, beginning on page 143).

While remaining true to the magazine's title, the authors and editors responsible for the current issue of **impact** have dipped extensively into the currents and eddies of the flow of progress in scientific discovery in biology, chemistry, physics, and mathematics. Readers not familiar with developments in these fields will thus find the going a little hard in the articles by Jean-Claude Pecker, Jules Duchesne, Yuri Novozhilov, Aleksandr Baldin, and Charles Musès—but the rewards will be great. In an analysis of what new learning means in terms of certain behavioural processes, Mircea Malita then calls for intensive scrutiny of the higher learning processes requiring self-organization.

A new discipline, biometeorology, is concerned with the relationship between natural physical factors (such as those found in weather science), ambient physico-chemical systems of various kinds, and living organisms—including the human body. John Tomblin and Adriaan Volker deal with the translation of our current knowledge of various scientific phenomena in two broad fields of immediate interest to all who inhabit our planet: the management of continental water resources and the prevention and control of various geophysical cataclysms.

It would seem, despite our cautionary words in the first paragraph, that even this issue does not wander too far from its usual preoccupations with the mutual pertinence of scientific research and the human condition. As one finds in the ancient Japanese conception of duty and humanity (or compassion), *giri ninjó*, there is inherent in contemporary scientific endeavour a sense of social obligation—morality, if you prefer—that hopefully will be able to dominate the baser instincts leading us sometimes to misuse, if not abuse, the scientific enterprise.

Some future changes

Returning to our editorial poll of the readership, we should note that reader response was impressive. Although it is interesting to compare the minor cultural differences suggested by the answers received from the English-speaking and French-speaking readerships, the trends of all replies are remarkably similar among the first nine questions of the questionnaire circulated. We are especially grateful to those who took the time and pains to reply subjectively to the tenth, open-ended question; we are publishing, for the edification of all readers, some of the typical reactions we received to this question. Some of the suggestions made by readers are already incorporated in our planning of future issues; indeed, a list of future themes, being prepared for the coming year, is included at the back of the present issue.

For those of our readers who prefer our editions in the Arabic, Portuguese or Spanish languages, we hope, in due time, to be able to present comparable readership analyses for each of those versions.

Some readers have expressed the desire to see included in our editorial portfolios subject-matter which cannot—because of lack of space, infrequent periodicity, or the aims and missions of an intergovernmental organization—be included. 'Short notes about science today' is one of these. We cannot compete with the highly successful weekly journals, *Nature* and *Science*, in handling the news of science. '... One issue devoted to one subject... destroys variety.' Here again, the monthly and semi-monthly journals *(La Recherche, Die Naturwissenschaften, Nauk i Zhizn, Scientific American)* are better placed to handle non-thematic subject-matter. Science fiction has been suggested for treatment; although it has little to do with the problems of science and technology applied to development—Unesco's main concern in science—the readers who suggested science fiction may be pleased to learn that a theme on our planning list is, 'Science Fiction and Visions of Future Worlds'.

We have many requests for back issues, some of which are exhausted. Readers who desire issues antedating 1973, all of which exist in reprint, can get in touch with: Kraus Reprints, FL 9491 Nendeln, Liechtenstein.

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To delve more deeply

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The frontiers of the astronomical universe

Jean-Claude Pecker

The author reviews the current state of knowledge obtained by means of observations using the increasingly powerful or proficient instruments of astrophysics, radio astronomy and space astronomy (astronomy by satellite). In conclusion he refers to certain mathematical entities introduced into the theory of the origins and evolution of the cosmos.

It is not in the author's intentions to say whether space is finite or infinite, whether time has always been passing or is of but recent origin, whether the universe has or does not have limits, whether matter was created at a given moment or is continually being created or, quite simply, has always existed. Nor is he prepared to introduce quasi-metaphysical elements into astronomy, and he asks the reader to excuse him his pragmatism: for him, astronomy is first and foremost a science of observation. And any research worker seeking knowledge of that which can be observed must start out from that which is observed. As for the rest, what can be said about it? We shall, in conclusion, refer to certain mathematical entities introduced into the theory of the universe—cosmological theory—whose heuristic character is today being put to use. But we shall first of all endeavour to take stock of what has been revealed to us to date through observation using the ever-more powerful or proficient instruments of astrophysics, radio astronomy and space astronomy.

Extending the field of observation

It would take too long to give a detailed account of the new techniques available, so we shall make do with pointing out their current limitations.

Each celestial body in the universe emits rays of light which are perceptible by the observer on earth and which, when they reach him, have been weakened by distance and modified by the media through which they have passed. Astronomy consists in the analysis of these rays. Admittedly, it is difficult to form an accurate picture of the universe on the basis of this fragile and tenuous message, and progress is slow. Should other sources of information perhaps be sought? Recourse may be had to cosmic rays, for instance. The particles of energy released through primary cosmic radiation provide us with a certain amount of information, but of a highly limited kind.

When better methods of detection and measurement are available, it will perhaps be possible to gain further information through the detection of gravitational waves from infinite space, but we are a long way from that yet. Perhaps terrestrial physics and the values of universal constants should also be brought to bear in an attempt to focus on the very structure of the universe: does not the principle of Mach tell us that the whole of physics, in any place in the universe—on the earth for instance—is closely bound to the

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structure of the universe as a whole and with mass distribution in the universe? True, the principle of Mach is an attractive philosophical idea which could make it possible to conceive of the universe on a unitary basis and perhaps to construct cosmologies, but in practice there is little ready use that can be made of it.

We must therefore resign ourselves to the fact that photons, the particles of infinitesimal mass which make up light, are indeed the only messengers that provide the observer on earth with signals from the furthermost reaches of the universe.

The photons which reach us, astronomers on earth, are, however, limited in number: all the media through which they have to pass, and principally the earth's atmosphere, obstruct a considerable quantity of them. The diagram in Figure 1 shows the wave-length (or frequency) zones observable from the earth and those which have to be observed from space vehicles—the region of high-energy gamma rays, that of X-rays, that of ultra-violet rays and that of infra-red rays. But just as the earth's atmosphere conceals from us part of the sun's radiation, so a considerable part of the radiation from the stars—ultra-violet—is concealed from us by the interstellar medium. And the space astronomer cannot directly observe the high-energy radiation of the stars, which is transformed by absorptions followed by cascades into radiation of greater wave-length and lower energy. However far from earth space vehicles are able to penetrate space (even assuming the possibility of intergalactic travel, which is in the realm of science fiction), it will never be possible to observe a substantial proportion of photons in any manner other than indirectly.

The omnipresent visual ray

The number of photons from a source is variable; a celestial body may appear bright or scarcely visible. Naturally, it is possible by means of powerful instruments to distinguish faint bodies; however, a great deal of stray light exists which limits the range of the telescopes used on earth. The sky diffuses the light of the stars and has its own radiation, and this radiation which is diffused or emitted by air molecules masks radiation emitted from sources beyond the sky. Space probes, it is true, provide a means of overcoming the effects of stray radiation in the earth's atmosphere; but the earth belongs to the solar system and this system, within space, is a concentration, a disc of diffusing dust, which surrounds the planets on all sides. Even for an observer placed in a satellite, zodiacal light imposes a limit on the magnitude of the faintest star which it is possible to observe. And if this is true in the visible or ultra-violet region it is true *a fortiori* in the infra-red region, where the specific radiation of the precision instruments used remains intense since it is not possible for them to be cooled down sufficiently. We may add that, at the moment, thought is being given to placing in space telescopes of approximately 2 m only, almost ten times smaller than the telescopes used on earth. Figure 2 shows the range of the principal known instruments: are there still stars of interest beyond the twenty-sixth magnitude? Or do we then find ourselves close to a cosmological 'horizon'? We shall return to this question—a metaphysical one again—in the conclusion to this study.

The universe from which these photons come to us is immense, filled with stars, galaxies, planets and dust, puffed with gas, atoms and molecules of every kind. Each time that an instrument's range is increased, or it acquires greater possibilities of focusing on this or that region of the spectrum, new components of the universe are discovered. A celebrated paradox put forward by Loys de Chéseaux in 1743 (in his *Traité de la Comète*), and subsequently discussed by Olbers—whose name it bears—brings out an important aspect of this almost obvious truth. In whatever direction one's gaze is directed, to a near or distant point, the visual ray is bound to encounter a radiating surface (that of a star, for instance). Now the brightness—the apparent magnitude by square solid

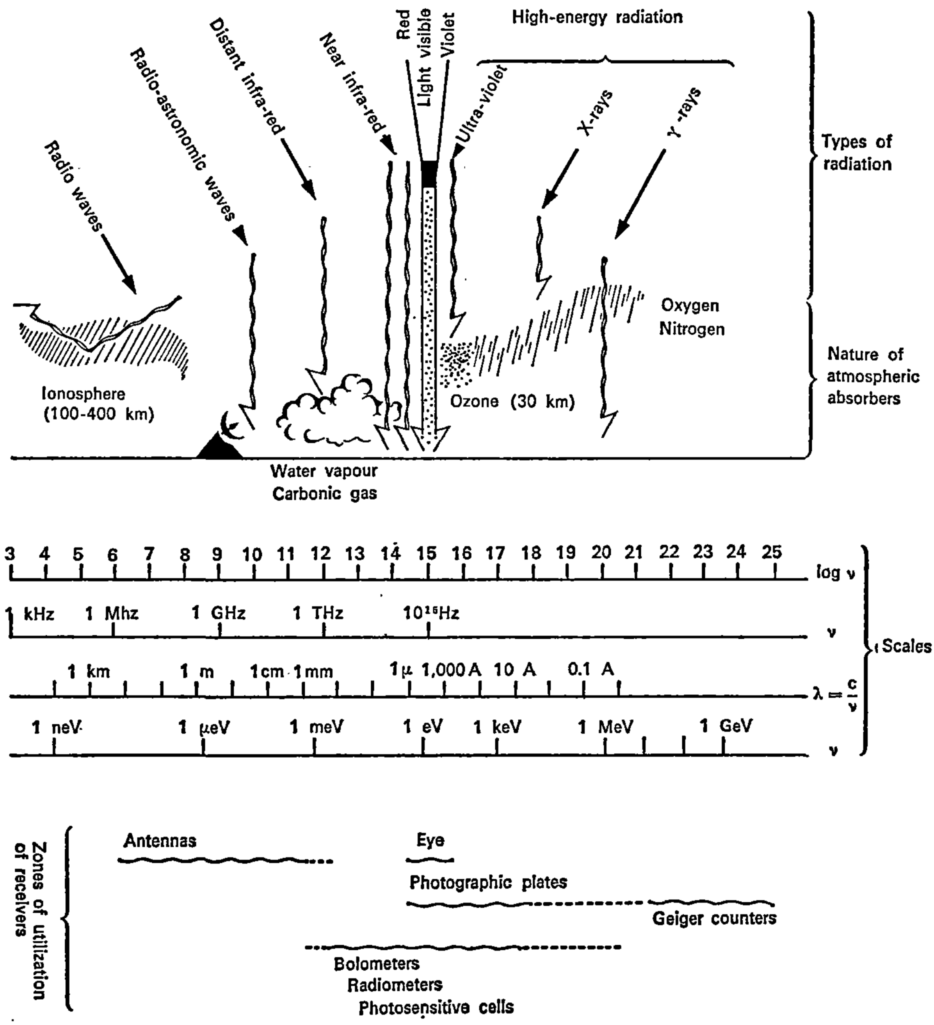


Fig. 1. Scale of frequencies and wave-lengths.

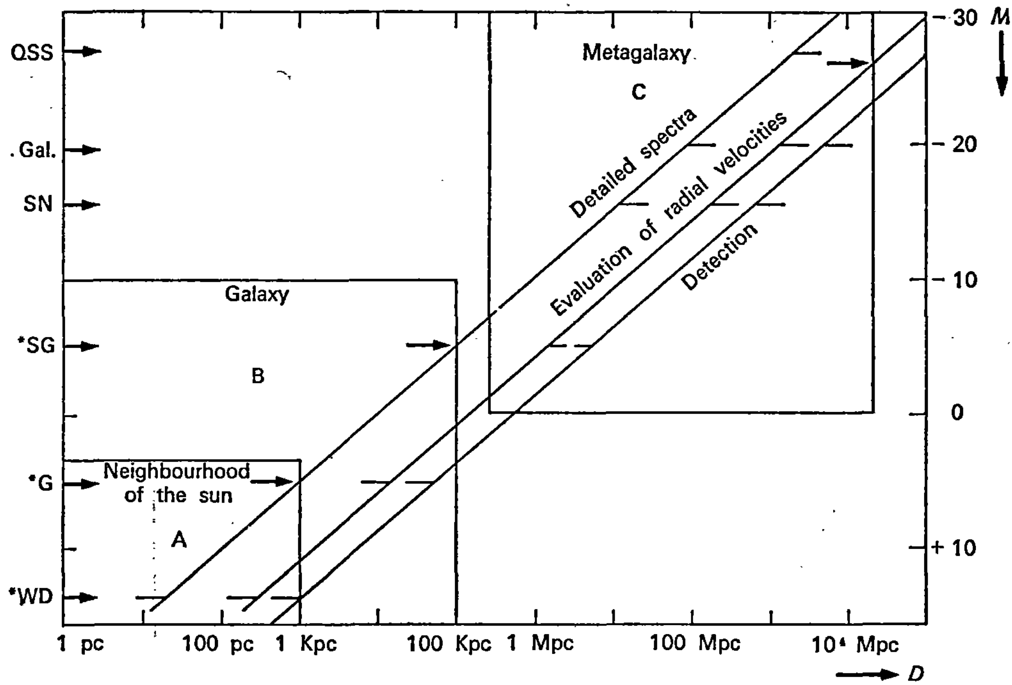


FIG. 2. The range of a large instrument.

For a telescope such as the 5-m telescope on Mount Palomar, or the 6-m telescope at Zelenchuk (U.S.S.R.), the distance at which it is possible to obtain a good spectrum, measure radial velocities, or simply detect a celestial body, depends on the absolute magnitude of that body. It is thus clear why it is that the limit of quasars for which a single radial is known is that of the observable universe; beyond, a quasar is detectable; but how can it be known to be one? On the *y*-axis, left, the positions of a typical quasar (QSS), a galaxy, a supernova (SN), a supergiant (SG), a star like the sun (G) and a white dwarf (WD).

angle—of a luminous surface is independent of the distance at which it is situated; one should therefore see everywhere a light comparable to that of the sun. If one were to pursue this argument to its logical conclusion, it would consequently be inconceivable for the sky to be dark.

The fact that the sky does become dark, while harbouring infinite depths, is a fact known by experience which our conception of the universe must take into account. For two centuries reflection on Olbers' paradox has provided material for models of the universe with the result that many things have been discovered. But it would perhaps be fitting, before delving into infinity, to describe, one after the other, the essential stages leading towards these distant and obscure horizons.

The hierarchic pattern of the observed universe

The universe as we see it is a strange assemblage: simultaneously we receive light from near-by heavenly bodies which has taken a few seconds to reach us (the moon), a few minutes (the sun), a few hours (the distant planets), a few years (the nearest stars) and tens of thousands of years (the other regions of the galaxy), together with light from far more distant bodies, which set out millions of years ago (other galaxies, those closest to us), or even

TABLE 1. Size, mass and distance of celestial bodies, from the planets to the limits of the universe[1]

	Size (radius)	Mass	Distance
• Earth ⊕	$R_\oplus = 6{,}371$ km $= 0.011\, R_\odot$	$M_\oplus = 5.98 \cdot 10^{27}$ g $= 0.000003\, M_\odot$	We are there!
• Moon ☾	$R_{☾} = 1{,}738$ km $= 0.27\, R_\oplus$	$M_{☾} = 7.34 \cdot 10^{24}$ g $= 0.0012\, M_\oplus$	$3.84 \cdot 10^{10}$ cm
• Mars ♂	$R_{♂} = 3{,}400$ km $= 0.53\, R_\oplus$	$M_{♂}$ $6.4 \cdot 10^{26}$ g $= 0.107\, M_\oplus$	0.7 to $3.7 \cdot 10^{13}$ cm
• Sun ⊙	$R_\odot = 6.96 \cdot 10^{10}$ cm $= 91\, R_\oplus$	$M_\odot = 1.99 \cdot 10^{33}$ g $= 33{,}000\, M_\oplus$	$1.496 \cdot 10^{13}$ cm
• Jupiter ♃	$R_{♃} = 71{,}400$ km $= 11.2\, R_\oplus$	$M_{♃} = 1.9 \cdot 10^{30}$ g $= 318\, M_\oplus$	6.3 to $14 \cdot 10^{13}$ cm
• Pluto ♇	$R_{♇} = 7{,}200$ km $= 1.14\, R_\oplus$	$M_{♇} = 5.4 \cdot 10^{27}$ g $= 0.9\, M_\oplus$	Approximately 10^{14} cm
• Proxima Centauri	$0.6\, R_\odot = 4.2 \cdot 10^{10}$ cm	$0.5\, M_\odot = 10^{33}$ g	1.3 pc $= 4 \cdot 10^{18}$ cm
• Sirius	$1.8\, R_\odot = 1.25 \cdot 10^{11}$ cm	$3\, M_\odot = 6 \cdot 10^{33}$ g	2.65 pc $= 8 \cdot 10^{18}$ cm
• Centaur cluster	90 pc $= 2.7 \cdot 10^{20}$ cm	$2 \cdot 10^{5}\, M_\odot = 4.10^{38}$ g	4.6 kpc $= 1.4 \cdot 10^{22}$ cm
• Centre of the galaxy	(undefined)	(undefined)	8 kpc $= 2.5 \cdot 10^{22}$ cm
• The galaxy (G)	25 × 5 kpc × kpc $= 7.5 \cdot 10^{22}$ cm $\times 1.5 \cdot 10^{22}$ cm	$1.5 \cdot 10^{11}\, M_\odot = 3 \cdot 10^{44}$ g	We are there.
• Large Magellanic Cloud	5 kpc $= 1.5 \cdot 10^{22}$ cm	$10^{9}\, M_\odot = 2 \cdot 10^{42}$ g	45 kpc $= 1.3 \cdot 10^{23}$ cm
• Andromeda galaxy	27 kpc $= 8 \cdot 10^{22}$ cm	$1.5 \cdot 10^{11}\, M_\odot = 3 \cdot 10^{44}$ g	500 kpc $= 1.5 \cdot 10^{24}$ cm
• Local group of galaxies	500 kpc $= 1.5 \cdot 10^{24}$ cm	$\sim 10^{13}\, M_\odot = 2 \cdot 10^{46}$ g	We are there.
• The coma cluster of galaxies	0.7 Mpc $= 2 \cdot 10^{24}$ cm	$1.7 \cdot 10^{15}\, M_\odot = 3.5 \cdot 10^{48}$ g	130 Mpc $= 4 \cdot 10^{26}$ cm
• A galaxy of the twentieth magnitude	20 kpc $= 6 \cdot 10^{21}$ cm	$10^{10}\, M_\odot = 2 \cdot 10^{43}$ g	10 Mpc $= 3 \cdot 10^{25}$ cm
• The supergalaxy	40 Mpc $= 1.2 \cdot 10^{26}$ cm	$10^{15}\, M_\odot = 2 \cdot 10^{48}$ g	We are there.
• Horizon of observations of galaxies[2]			7,000 Mpc $= 2 \cdot 10^{29}$ cm
• The most distant (QSS)[2]	A few pcs $\cong 10^{19}$ cm	$\sim 10^{7}\, M_\odot = 2 \cdot 10^{40}$ g	60,000 Mpc $= 2 \cdot 10^{30}$ cm
• Observable universe	$\sim$ 60,000 Mpc $= 2 \cdot 10^{29}$ cm	$\sim 10^{21}\, M_\odot \cong 2 \cdot 10^{54}$ g ($\cong 10^{10}\, M_{\text{Galaxy}}$)	We are there.

1. In this table are shown, in conventional units, the size, mass and distance of various objects in the astronomical universe. It is to be recalled that reference is often made to the mass and radius of the earth and of the sun; it is also to be recalled that 1 pc $= 3.085 \times 10^{18}$ cm and that 1 pc $= 3.26$ light-years. Generally speaking, the numbers given by this table are, with a few exceptions, orders of magnitude which become less and less reliable from the top to the bottom of the table.
2. Distance computed with $H = 50$ km/s/Mpc and assuming the 'cosmological' distance of quasars (QSS).

thousands of millions of years ago (the furthermost galaxies we know are thousands of millions of light-years away) (Table 1). Ours is a composite sky of which we can form an accurate picture only by correcting those distortions, more or less successfully. At all events, comparisons between near-by celestial bodies and distant ones reveal to us that as those which are furthest away have properties comparable to those of the nearest ones (there were no *a priori* grounds for believing this to be obviously so: the case of quasars is perhaps an exception to this rule—we shall come back to it), these properties are fairly well defined in so far as the distant universe does not appear to be too different from the near universe; the laws of physics do indeed seem to be universal, and this fundamental discovery authorizes the astronomer to use physics to describe his observations.

The universe, as it is, consequently reveals to us an essentially hierarchic structure (Fig. 3). This means that planets group themselves around a star, forming planetary systems; that stars group themselves into clusters; that even larger families of stars and clusters form quite definite and fairly stable systems, galaxies; that galaxies, like stars, group themselves into clusters of galaxies; and, lastly, that these galactic clusters themselves form clusters of clusters, or supergalaxies. Of these supergalaxies, only a few at most are known, but it can be shown that the limitation of our instruments is such that it would not be possible to detect a greater number within the observable universe.

This hierarchic universe possesses strange peculiarities: each of its elements is enveloped in a less dense medium—the stars in an interstellar medium, the galaxies in an intergalactic medium—and the difference between the density of the external medium and that of the astronomical object enveloped in it grows less and less pronounced as one approaches the largest systems. Extrapola-

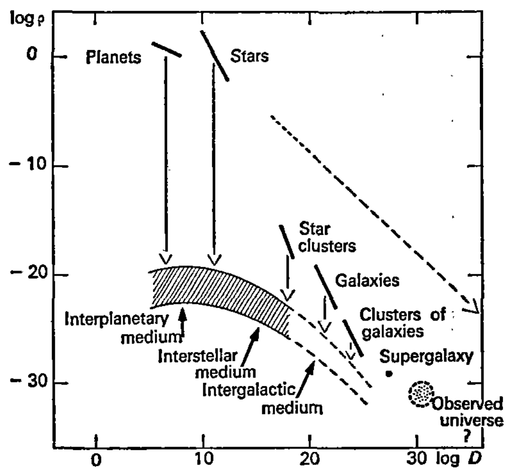


FIG. 3. The hierarchic universe.

On the x-axis the logarithm of distance, on the y-axis that of density. The dotted line shows the gradient (according to Charlier) such that if the relation log ρ–log D is more sloping, as is the case, Olbers' paradox disappears. It will be noted that irregularities are less and less pronounced the greater the scale.

tion is scarcely possible and we shall confine ourselves to that which can be observed. But the following question may legitimately be raised: would true homogeneity be found on a scale greater than that of the observable universe? Does the hierarchic structure come to an end at a particular level? For the time being, there is no possible answer to this question.

It is also interesting to note that, in a hierarchic universe, the density of a volume (for instance, the ratio of the mass of a sphere of a radius r to its volume $4/3\,\pi r^3$) decreases when r increases. If r is sufficiently large this density may be far smaller than that of the interstellar medium, or even of the intergalactic medium, as measured in the vicinity of our own galaxy (that is to say, within our supergalaxy). For similar reasons, and provided that the relation between ρ and r to be found in the observable universe ($\rho \propto r^{-2.7}$), is maintained to infinity, Olbers' paradox is resolved. (This was shown by Fournier d'Albe and Charlier at the end of the last century.) It has been demonstrated since that the existence of a hierarchic universe, while making it possible to resolve Olbers' paradox, is not the only solution possible: for other reasons—interstellar and intergalactic absorption, Hubble's law—the furthermost reaches of the sky must be nonluminous. But Olbers' paradox, by drawing the attention of theoreticians, and then of observers, to hierarchic universes, has at least the historical merit of obliging us to accord a deep-seated significance to this hierarchic system.

The galaxies

Let us now take another look at the elements of this hierarchic universe. Let us decide to consider as the heavenly body which best provides an illustration of the advance of contemporary astrophysics not the sun, that near luminary, nor a given star, as we would no doubt have done thirty years ago, nor a given supergalaxy as we shall perhaps do in thirty years' time but *the* galaxy, our galaxy, and its sisters, the galaxies.

When one observes the sky with the naked eye, or with a small instrument, all that one can see are stars. If, on the other hand, one uses a large telescope, one observes, as though through the meshes of a net, distant galaxies which are even more numerous than the near stars and which, in contradistinction with the stars, do not appear as mere luminous dots: the galaxies have perceptible forms, frequently simply elongated in one direction; this feature has often caused them to be called by the name of nebulae. For a long time they were confused with the near, gaseous nebulae to be found within our own galaxy. The history of the advances we have made in assessing the distances of the galaxies is of great importance in so far as it makes perfectly clear the nature of the advances achieved in our knowledge of the universe.

It was in the eighteenth century that it began to be realized that there existed in the sky, in addition to stars and planets, objects with vague outlines, of non-zero apparent size, and possessing fixed forms. The first catalogue of such objects, that established by Messier, contained more than a hundred nebular objects. These included star clusters, belonging to our galaxy and relatively near—some few thousands or tens of thousands of light-years distant—and gaseous nebulae, like that of Lyra, also belonging to our galaxy, but also objects such as the Andromeda Nebula and other nebulae, spiral in shape, which in Messier's time no one thought of distinguishing particularly from the others. Even recently, astronomers as clear-sighted as Harlow Shapley, around 1914, thought that most nebulae, whether spiral or otherwise, were in actual fact fairly small in size and that they belonged to our galaxy, just like the better-known star clusters.

It is possible indeed by means of trigonometric methods to measure distances, but only within a limited range. This is done by measuring the change in the apparent direction of a star in the course of the year, by reference to the distant fixed stars (Fig. 4). The angle subtended at the star by the mean radius of the orbit of the earth is the parallax. The distance of a star whose parallax was one second of arc would, by definition, be one parsec (pc), equal to 3.26 light-years. The parsec can also be expressed as $1 \text{ pc} = 3.09 \times 10^{18}$ cm. In fact the nearest stars have parallaxes of less than one second; in other words they are more than 1 pc distant. It is difficult to measure parallaxes: at best, accuracy of the order of a few thousandths of a second can be obtained. This means that it is possible to explore correctly a sphere with a radius of a few hundred pc within our galaxy, as it were the suburbs of the solar system. For greater distances—be it a question of stars within our galaxy or nebulosities of all kinds—it is necessary to resort to indirect measurement; and the methods used are sometimes very chancy.

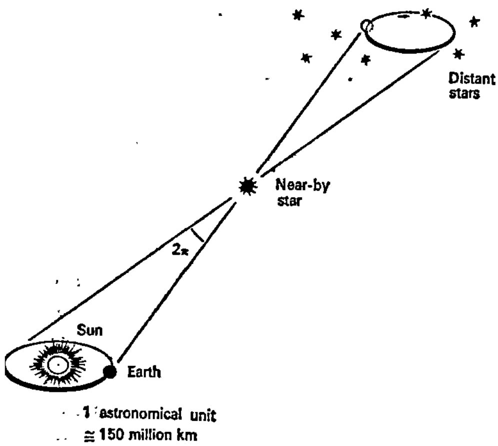


FIG. 4. Measurement of the distance of a near-by star.

A near-by star seems, during the earth's revolution around the sun, to describe an ellipse, in relation to the distant stars. The apparent size of this ellipse makes it possible to determine the angle 2π subtended at the near-by star by the mean diameter of the earth's orbit; π is the parallax of the star; $D = 1/\pi$ is its distance expressed in parsecs, if π is expressed in seconds.

The period–luminosity relation

Although the first measurements of parallaxes date from the 1830s and the years immediately following, it was already being suspected, on the basis of certain intuitions, that all of the known stars, and those of the Milky Way (which was seen to be made up of stars as early as 1610 by Galileo), formed an isolated family in the universe. This idea (founded perhaps in part on Olbers' paradox) was subscribed to in particular by astronomer philosophers such as Immanuel Kant and William Herschel. They thought that the visible stars formed an 'island universe' (of which the sun, so they believed, occupied almost the centre), and that there existed here and there other island universes, of which certain nebulae could be examples.

It was necessary to wait for Hubble for the distances of certain galaxies—the Andromeda Nebula, the Magellanic Clouds—to be more or less correctly ascertained. Hubble's work was based on a study by Shapley and Henrietta Leavitt; these researchers, by studying the variable stars (called cepheids) of the Magellanic Clouds, had established a relationship between the period of pulsations of these stars (which period is of course independent of their distance) and their apparent brightness (Fig. 5). This relationship could also be considered as one between the period of these stars and their absolute brightness (luminosity)—since it was permissible to regard all the stars of the Magellanic Clouds as being at the same distance from us. True, the 'zero point' of this relation, defined to the nearest constant, was not known, since this constant was linked to the unknown distance of the Magellanic Clouds. But, at all events, it was possible, by considering in terms of this

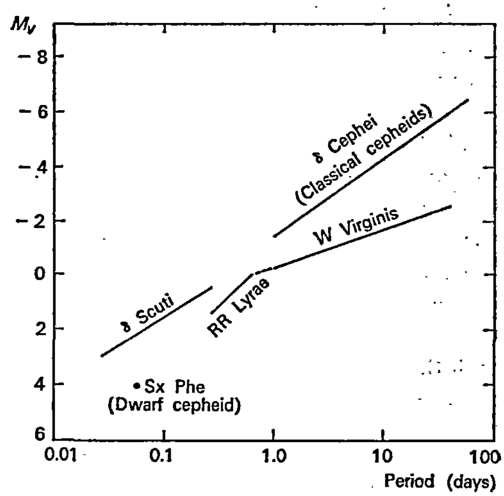


FIG. 5. The relation between the period and the luminosity of pulsating stars.

On the x-axis, the period (logarithmic scale); on the y-axis, the absolute visual magnitude (for the relationship between absolute magnitude and luminosity, see footnote on 2 page 16). It will be seen that there is a clearly marked difference between the behaviour patterns, for the same period value, of stars such as the classical cepheids and the W Virginis; they are easily made out by the shape of their light-curve, thus avoiding all ambiguity; the physical characteristics of the pulsation differ from case to case.

relation other nebulosities in which identical variable stars were to be found, to compare their distance with that of the Magellanic Clouds. This was what Hubble did, measuring the periods of cepheids observed in the Andromeda Nebula. The distance of the Andromeda Nebula was consequently found to be great, and there was no way of denying the facts: the nebula was indeed extragalactic. It followed that all the spirals observed in the sky by astronomers using large telescopes were extragalactic.

It is impossible here to give a detailed account of the indirect measurements of distance which have made it possible, on a step-by-step basis and using various standard 'candles', to know the distances of more remote galaxies. However, these techniques are not completely reliable; for example, it is in any case clear that the smaller a galaxy seems, the less bright it appears and the further away it is; but this presupposes that the galaxies are identical to each other, and such is far from being the case. The diversity of the galaxies, as regards their shapes, brightness, size and colours, is in fact as great as the diversity of the stars within a single galaxy, and perhaps even greater.

Hubble's law

The universe of the galaxies obeys a strange law and one which has dominated the field of astrophysics for fifty years, namely Hubble's law. During the 1920s, Slipher, the great spectographer, photographed and measured a large number of galaxies. Their spectra all possessed a noteworthy characteristic—the ultra-violet doublet of ionized calcium which can easily be recognized and which is to be found in an intense form in the spectra of most of the stars in the galaxy, and in particular in the solar spectrum. However, while this doublet was found by Slipher in all the extragalactic objects studied, it was, generally speaking, marked, to a measurable and often great extent, by a shift towards the red, as it would be if the object measured were receding from the earth at a velocity of $v = c\,(\Delta\lambda/\lambda)$, where c designates the velocity of light, λ the wavelength of one of the spectral lines measured and $\Delta\lambda$ the red shift in respect of that line.

By means of cepheids and novae, Hubble had already measured the distance L of numerous galaxies; it was only natural that he should compare the red shift and the distance. And when he did so, he discovered a law of proportionality: the velocity of apparent recession (v) of a galaxy is proportional to its distance L. This law is expressed as follows: $v = HL$, where H is 'Hubble's constant' (Fig. 6).

Admittedly (and Hubble laid great emphasis on this point) what was involved was only the apparent velocity, and perhaps this was not directly related to its real velocity of recession.

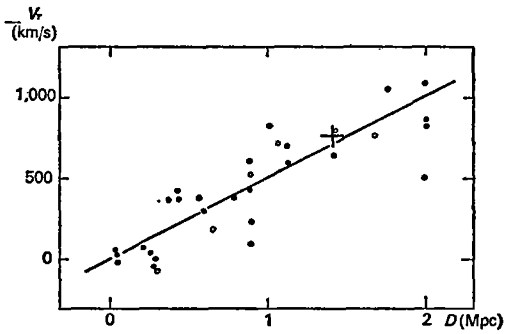


FIG. 6. Hubble's diagram (1929).

This figure (based on Hubble's original) shows the variation in velocity as a function of distance; estimates of distance were underestimated at that time by a factor of around 10. The black dots correspond to individual values, the circles to the means of several dots, the cross to the mean of a number of faint galaxies.

This discovery was confirmed in an increasingly convincing manner by Hubble and his successors; Hubble's constant has been calibrated, decalibrated and recalibrated for fifty years as advances have been made in knowledge and in the utilization of criteria of distance; it is accepted now to have a value of 55 km per second per megaparsec

(1 Mpc = 1 million pc). Measurements of distance whose progressive calibration is possible already allow fairly great distances to be attained: approximately 3,000 Mpc, or 1,000 million light-years. The indirect criterion of distance used for the greatest distances is the absolute brightness (luminosity) of the most luminous galaxies among the clusters of galaxies (Fig. 7).

Quasars[1]

For more distant objects whose distance cannot be determined by means of any criterion, as compared with nearer objects, Hubble's law was in fact, assuming it to be universal, to provide a measurement of distance. Thus was determined the distance of quasars.

What are quasars? Some twenty years ago radio astronomy, at last equipped with large-scale instruments with high resolving power, discovered radio sources which were virtually akin to point sources. Astronomers identified these objects with certain very faint optical sources in no way resembling a galaxy, but rather a faint star. They differed from near-by faint stars in that the latter did not emit any radio-frequency radiation. What then were these quasars?

After a great deal of searching it became obvious that what were involved were extragalactic objects. But it has to be admitted that their brightness scarcely provides a basis on which to estimate their distance since we do not know what to compare it with and we do not really know the distance of any quasar S. Whence the idea that quasars, extragalactic bodies, are situated at the exact distance implied by the red shift of their spectral lines, in short, at the distance attributed to them by Hubble's law, assumed to be valid for them as for all the galaxies. It is clear that quasars (Fig. 8) are, in terms of both their visible radiation and their radio-frequency radiation, extremely bright (an absolute magnitude[2] of around —25 to —27, as opposed to —20 or —21 for a nor-

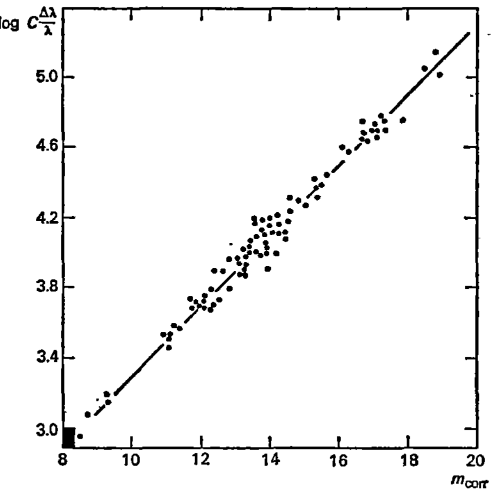


FIG. 7. Modern version of Hubble's diagram (based on Sandage, 1975).

On the x-axis, apparent magnitude corrected for absorption; on the y-axis, logarithm of spectral displacement. The brightest galaxies of clusters have been used, thus attaining shifts close to half the velocity of light. The black rectangle, bottom left, represents the content of Figure 6, thus giving an idea of the progress achieved over close on fifty years.

1. The abbreviation of 'quasi-stellar astronomical radio source'. One should therefore, strictly speaking, always write 'quasars' even in the singular, despite the more common 'a quasar'.
2. The relation between luminosity L (the energy M radiated by the star or galaxy per second) and absolute magnitude (its notional magnitude at a standard distance of 10 pc) is: $M = 4.6 - 2.5 \log £/£\odot$ where $£\odot$ is the luminosity of the sun ($£\odot$ = 3.86×10^{33} ergs per second). Absolute magnitude M (called here absolute bolometric magnitude) is linked to apparent magnitude M by the relation: $M = m + 5 + 5 \log \pi - A$ where π is (in seconds of arc) the parallax and where A measures (in units of magnitude) the interstellar or intergalactic absorption. Bolometric magnitude and photovisual (usual) magnitude are linked by the relation $m_{pv} - m_{bol} = BC$. The bolometric correction BC depends solely on the distribution of energy in the spectrum; it is a positive quantity which may attain a few magnitudes.

mal giant galaxy). This is a difference of 5 to 7 magnitudes, i.e. a factor of 100 to 1,000: and yet very small and of slight mass (which seems to be proved by the existence of fairly rapid variations in the brightness of all the quasars).

The expanding universe and the Big Bang

The accepted universality of Hubble's law was bound to lead *a priori* to its being assigned a precise physical significance. And this has long been the case, despite the circumspect reservations of observers such as Hubble or certain theoreticians such as Tolman. Since the relativistic theory of Abbé Lemaître, 'models' of the universe have in fact been built. We shall come back to these, as we have already said. These models interpret Hubble's law as an indication of an expanding universe in which the galaxies and quasars observed turn out in the end to be no more than the equivalent of buoys, carried away upon an immense ocean at a velocity equal at each point to that of the recession of this vast expanding universe.

From expansion to explosion is a very short mental step, soon taken. Starting from the idea of an expanding universe one arrives at a point which can be postulated as the origin of that universe. And of course, such an idea has not surprisingly led to passions being unleashed on all sides, under the more or less marked influence of individual metaphysical and philosophical conceptions. The fact remains that, following the theory of the expanding universe (curiously defended by Pope Pius XII in his *Address to the Astronomers* of 1952), efforts were made to formulate the theory of the 'Big Bang'—the initial explosion of what Lemaître called the primordial atom. One of the predictions from these models, made by Gamow, was that one should observe—as the so-to-speak fossil remains of a primordial universe raised to a considerable temperature—an infra-red radio radiation corresponding to that which

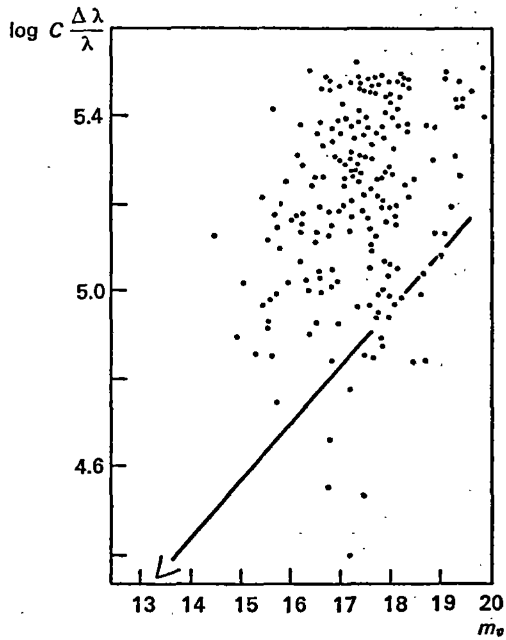


FIG. 8. Quasars in Hubble's diagram.

The straight line represents Hubble's law. Same axes as in Figure 7. The extremely scattered character of the dots will be noted—corresponding, if it were expressed as a dispersion of absolute magnitudes to more than 5 magnitudes. Another interpretation of this dispersion is that the red shifts are not of cosmological origin.

would be observed if one were to be plunged into an oven at a temperature of a few degrees of thermodynamic temperature. And some years after Gamow had made this prediction, the radiation in question was in fact observed (Penzias and Wilson, 1865, at a temperature of 3 K (Fig. 9)). Once this predicted radiation—immediately christened 'cosmological radiation'—had been observed, the Big Bang theory was eagerly embraced. Moreover, this theory provided further grounds for satisfaction. In the great, original crucible, elements such as helium or deuterium were able to be formed: rapid cooling, as it were, hardened the nuclei, which would consequently be present in newly formed galaxies. No other theory makes it possible to explain why deuterium and helium are so plentiful in the stars of our galaxy.

The sum total of observations of every kind is thus very well represented by this theory which takes in Hubble's law, cosmological radiation at 3 K, and the chemical composition of the galaxies.

A few difficulties: abnormal red shifts

Unfortunately for this splendid harmony, numerous facts (which can however be challenged and which consequently are so) have come to light which contradict some of the provisional evidence accumulated by observation.

First of all, Hubble's law is not completely verified and can only be taken as a mean indication. Some galaxies often have greater red shifts than their distance would lead one to expect (Fig. 10). Sometimes what are involved are galaxies belonging to groups; the spectrum of one member of the group reveals a distinctly greater red shift than the others and to such an extent that it cannot be explained by any real relative movements within the group. Sometimes, what are involved are galaxies located behind particular clusters of galaxies. Sometimes, in groups of galaxies, the most compact ones are characterized by red shifts. Once, then, Hubble's law is acknowledged to be only a mean law, the quasars once again raise a serious question. The only basis on which their distances can be estimated is, as we have said, Hubble's law, but it is patently obvious that they are strange objects. And what if there were some single reason for the slight additional shift of galaxies situated behind clusters, the abnormal, greater shift of galaxies in groups, and the enormous shift characterizing quasars? The consequence of this could be to knock quasars off the pedestal on which they have been set by virtue of their being regarded as the brightest celestial bodies. If they were to be brought nearer by a factor of 100 in distance, their brightness would decrease by a factor of 10,000, and they would become less bright than the brightest of the galaxies.

The example of quasar 3C 279 is, in this connexion, highly instructive: this object and others of the same kind are double quasars; now it is possible to show by means of measurements that the two components of this quasar are receding from each other.

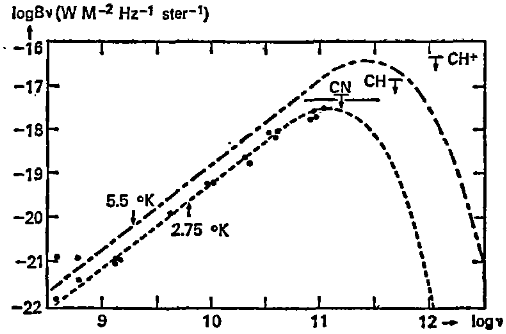


Fig. 9. Radiation from the furthermost regions of the sky.

On the x-axis, the logarithm of frequency; on the y-axis, the brightness of the sky, per unit of frequency. The curves correspond to two black bodies at 2.75 K and 5.5 K. The dots correspond to the measurements, the arrows to the estimates; upper limits fixed by observation tests relating to molecules CN, CH and CH+.

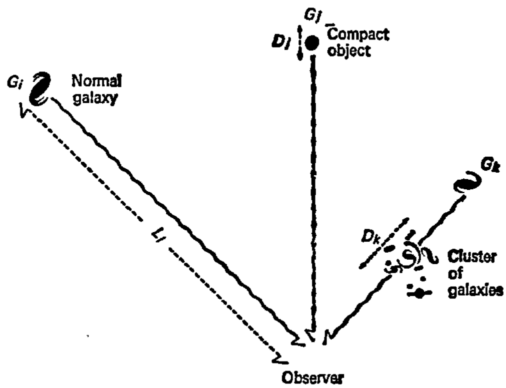


Fig. 10. Possible causes of red shifts.

On top of the normal Hubble effect, acting over the distance L_i of a galaxy G_i, is superimposed an intrinsic shift linked to the compactness of the source and depending on its size (and on its compactness), together with an additional shift caused by the ray of light having passed through clusters of galaxies.

If this double object is attributed the distance implied by Hubble's law, the recession velocity, projected on to the sky, is ten times the velocity of light! True, complicated and improbable situations can be imagined by virtue of which this velocity would not be a real velocity of matter, but that of the propagation of a wave; complicated geometrical situations can also be imagined in which relativistic terms may create the illusion of a superrelativistic velocity. But it may also be more naturally thought that there exists no velocity greater than that of light and that the theories in question are less probable than an error in the distance of quasar 3C 279. If such is the case for this object, then why should it not also be the case for all quasars? Why should their spectral shift not be intrinsic, caused by the same phenomena as those which cause the anisotropy of Hubble's constant and the red shifts in the spectra of compact objects? After all, quasars are more compact than any other extragalactic objects. A difference factor of 100 between the intrinsic red shift and the shift foreseen by Hubble's law thus reduces the distance of the quasars 100 times; it reduces hundredfold the apparent velocity of separation of double quasars and reduces their brightness 10,000 times: we thus find ourselves dealing with fields of energy more comparable to that of the energy emitted by the galaxies.

Now it so happens that certain strange galaxies are known which are surrounded on all sides by clouds of hydrogen that form extensive radio sources (for example, Centaurus A, Fig. 11). Other giant galaxies are known which seem to be the mothers of groups of symmetrical galaxies (Fig. 12), as though there had been an ejection in gaseous form and then condensation in the form of several associated galaxies. Is it not, therefore, natural to think that the phenomenon of ejection (arising perhaps, in the direction of the poles, from an excess of ultra-violet radiation resulting in an ejection of hydrogen through the pressure of the radiation) links up different extragalactic objects and that quasars and other more or less compact galaxies correspond to the state of a galaxy which has just been condensed and which is beginning (on account of the violent increase in its excessive ultra-violet radiation) to become active and even explosive? This would provide a plausible explanation for the observations, save for the fact that we still need to find a physical mechanism to explain abnormal shifts—those of quasars, those of compact objects and those of objects located behind a cluster of galaxies.

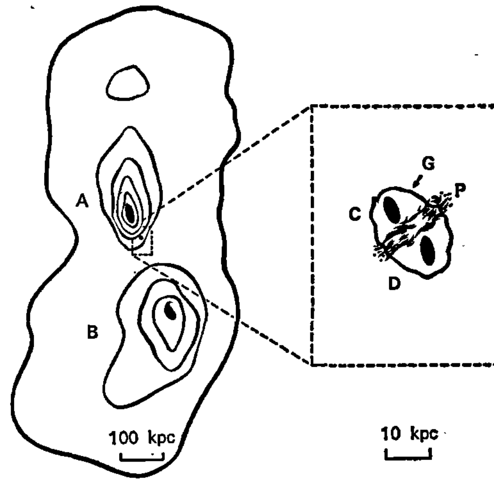


FIG. 11. The quadruple radio source Centaurus A. On the left, the object observed in radio astronomy, on a small scale; on the right, enlargement of the central area of the diagram on the left. A and B on the one hand, and C and D on the other, indicate the centre of the four symmetrical radio sources, by twos, in relation to the centre of galaxy NGC 5128. The outline of the very extensive corona of this strange galaxy is seen on the right (G); the very clear and intense belt of dust, visible on optical plates, which marks its equator, is designated by the letter *P*. The scales are indicated at the bottom, in kiloparsecs.

Photon fatigue?

Although, as has been said, these observations are very hotly debated, there is even greater scepticism with regard to the theories put forward to explain these abnormal shifts. There are many of them, too many for it to be possible to analyse them in detail. Our view, however, is that the solution is to be sought in a theory of 'fatigued light'. Photons, assumed to possess a certain mass (undoubtedly very small), might be regarded as entering into collision with hypothetical particles, designated by the symbol φ. The collision causes the photon to lose energy and to be deflected (globally, energy, momentum and spin are conserved: from this it follows that the particle φ takes away energy and is also displaced; and it must also be accepted that the mass of the φ is greater than that of the photon, but smaller than that of the electron, and that the φ has charge = 0 and spin = 1). For N collisions, the loss of energy (measured by the red shift) is proportional to N, and the deflexion to $\sqrt{N}$; if N is sufficiently large, the red shift may be quite pronounced, even if the deflexion is negligible, and consequently the images of distant objects will not be blurred. In addition, the density of the φ particles would be great in the vicinity of those regions of the universe where the density of matter is great: this would explain the effect of collisions on photons passing through clusters of galaxies, and also the excessive red shift in the spectra of compact objects, having high density both of matter and of φ particles. In the vicinity of masses of matter, the φ particles are virtually in equilibrium and their distribution is almost isotropic. If equilibrium exists as a result of the mutual transformation of a φ particle into two photons and vice versa, photons associated with the φ particles will be made as if it were isotropic: observed from the earth, they will produce a radiation which could well be of the order of 3 K. A fairly convincing argument in favour of this view of things (as against the cosmological origin of a 'fossil' radiation at 3 K) is that observation shows that this radiation is isotropic, whereas Hubble's rate of expansion is far from being so, as has been said.

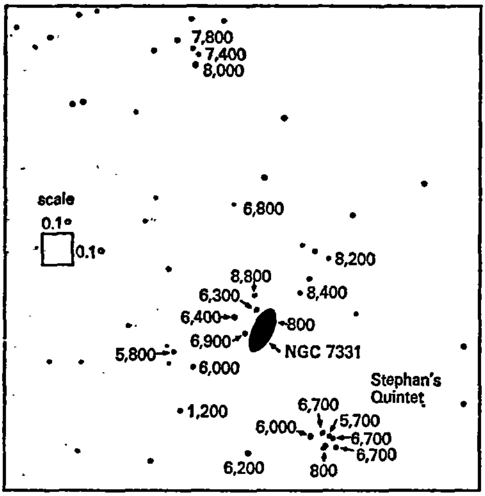


FIG. 12. The neighbourhood of galaxy NGC 7331.

The scale of this map of the sky is indicated on the left, half-way down. The figures represent, in km s^{-1}, the apparent recession velocities. The following will be noted: (a) Stephan's Quintet contains four objects whose velocity is of the order of 6,000 km s^{-1}, and one of 800 km s^{-1}, like the normal galaxy NGC 7331; (b) in the neighbourhood of NGC 7331, and, in particular, in a manner virtually symmetrical to Stephan's Quintet, are to be seen groups of galaxies with velocities of 6,000 to 9,000 km s^{-1}; (c) the other dots marked are near-by stars with a very small apparent velocity of recession (a few km per second).

Evolution of galaxies

In thus revising our conceptions, we have also clearly been influenced by the problems raised by the evolution of the galaxies (Fig. 13). Ejection from the poles is a phenomenon of which it can definitely be said that it follows from observation pure and simple, as can be seen in Figures 11 and 12. But one can also observe the accumulation of dark matter in the galactic plane, as well as, frequently, the fall towards the centre of our own galaxy of circumgalactic matter, neutral hydrogen responsible for radio emission in the hydrogen line at 21 cm.

These fundamental phenomena which take place on the very frontier of the galaxy, in the boundary zone between the galaxy and the intergalactic medium, are matched by internal features in the structure of the galaxy.

Thus the galactic corona regions, situated on both sides of the galactic plane, seem to be deficient in heavy elements, which have remained in the galactic plane, just as though the symmetrical ejection which originally disturbed the life of the galaxy had left some trace—ultra-violet radiation being conducive to the ejection of hydrogen alone.

Thus the galactic medium contains a very small number of very fine grains of dust; admittedly, their number is set higher (by means of probes in the ultra-violet region) than it used to be set (through the rational extrapolation of observations relating to the visible region); but their total mass is

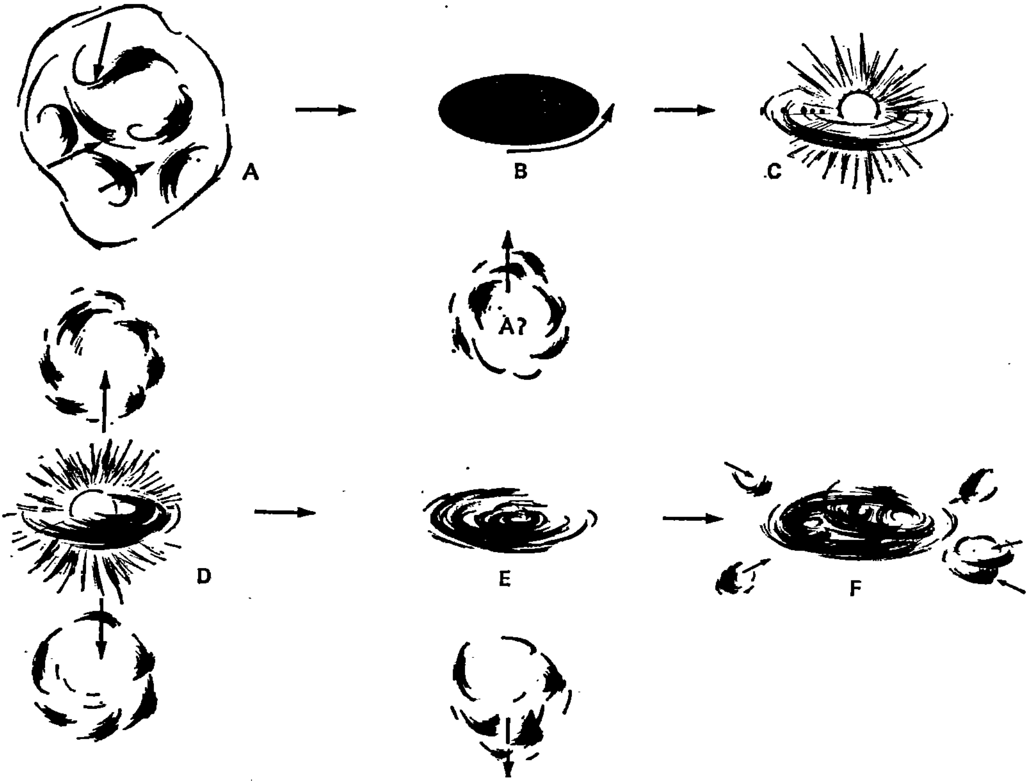


FIG. 13. Diagram of galactic evolution according to Pecker (1972).

A: amorphous, cold, extensive mass, undergoing gravitational condensation; B: the mass, scarcely condensed, turns on an axis (conservation of angular momentum) and is still cold; it is dense; C: stellar condensation, very rapid in this dense medium, takes place and produces very massive and bright condensations including a galactic nucleus—intense sources of ultra-violet. Is this a compact galaxy, or a quasar? D: the ultra-violet radiation more than compensates for the gravitation; there is instability; enormous masses of hydrogen are expelled from the polar regions at high velocity (somewhat in the manner of the source Centaurus A (Fig. 11); E: the ejected masses, confined by a weak magnetic field and compressed by the limitations imposed by their own optical thickness, become radio sources while the galaxy, calmed, becomes a normal galaxy; the ejected masses may behave like A and give birth to one or more galaxies (like NGC 7331 (Fig. 12); F: the galaxy is old, the ejections have disappeared—partly condensed into smaller galaxies, partly in the form of diffuse intergalactic matter. The galaxy, far from ejecting matter (no longer enough sources of ultra-violet radiation), ingests, through the equator, cloud masses (Dieter's ring): this is perhaps the stage which our own galaxy has reached.

limited, dust grains smaller than 10^{-6} cm in radius being expelled by the galaxy—at all events, having been expelled in an explosive phase. The grains observed now must have formed after the explosive phase.

In these evolutionary processes, the nucleus of our galaxy undoubtedly plays an important role: has it not been discovered that it regularly ejects masses of rapidly expanding gas and dust? The compact galaxies (N galaxies, or Seyfert galaxies) frequently have a substantial nucleus; a quasar may perhaps be identified with a galactic nucleus during the period of maximum activity of a particularly 'young' object.

Interstellar and circumstellar gas and dust

We thus see how study of the interstellar medium can be of invaluable assistance in furthering our knowledge of galactic evolution. This study has made great strides over the last few years through the development of spectrum analysis in astrophysical studies. The first important discovery was made some time ago when the existence of dark regions was noted in the galaxy—as though a cloud of dust concealed the stars situated behind it, and when also the gaseous character of galactic nebulae was recognized.

The study of these dark regions (absorption nebulae) as well as of the bright nebulae—reflecting the light of near-by stars or emitting light by fluorescence—led to interesting ideas concerning their nature (gas and dust) and their temperatures, which vary a great deal from one to the other. A strange world it is, one that contains these bright nebulae of ionized hydrogen at 8,000 to 10,000 K which, like the Orion nebula, surround a few families of very young stars like a fleecy cradle, alongside planetary nebulae ejected from some adult star, and forming around it an expanding, hot and gaseous ionized layer, and at the same time these cold clouds, at around 100 K, filled with thick dust.

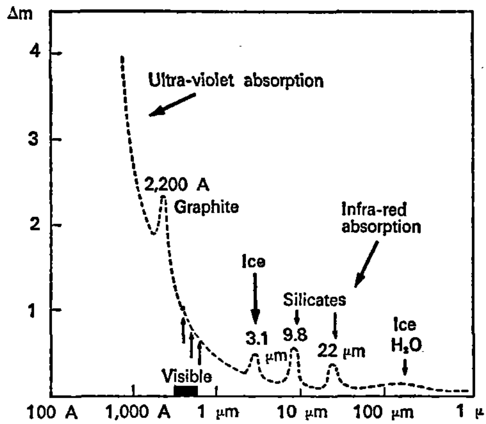


Fig. 14. Circumstellar and interstellar absorption

On the x-axis, the wave-length (logarithmic scale); on the y-axis, the absorption, in magnitudes, allowing for the extinction of 1 magnitude in the blue. The following will be noted: (a) the opacity, very pronounced in the ultraviolet; (b) the characteristic 'signature' of graphite, silicates and ice.

A considerable advance was made when the reddening (Fig. 14) of distant stars, caused by dust distributed through the galaxy, was discovered. This reddening (what is involved is not a displacement of spectral lines but a selective absorption in inverse proportion to the wave-length) is accompanied by general absorption: the reddened stars are less bright than identical stars not showing any reddening and which have the same luminosity. Naturally the reddening affects above all the areas in the vicinity of the Milky Way, that is to say, the regions of the galactic disc. It is to be noted that the change in colour due to absorption is independent of the regions observed (with a small number of exceptions, including the Orion stars); this fact proves that the size of the dust in the galaxy is virtually uniform. Perhaps it is to be understood by assuming that the dust was formed at the time that the galaxy originated and then was gradually dispersed: the stars retain, absorb and burn large grains of dust of a radius greater than 10^{-5} cm. Only a small number of them remain in orbit around the stars, and these form planets. The lightest ones, as has been said, were expelled from the galaxy which thus gradually divests itself of dust, retaining only those grains which are approximately 10^{-6} to 10^{-5} cm in radius. The study of spectra obtained in satellites confirms these views; it also makes clearer the nature of the dust by highlighting the graphite belt, at a wave-length of 2,200 A.

Where the galactic mass is situated

Infra-red radiation reveals the spectral characteristics of silicates and ice, which are other components of galactic dust. Ultraviolet and infra-red radiation bring out a new phenomenon: in addition to interstellar dust, there exist stars which are surrounded by circumstellar clouds whose composition may vary from one star to another, depending no doubt on the origin of these circumstellar shells. Some doubtless go back to before the formation of the stars, perhaps even to before the formation of the galaxy; they are the cradles of the stars which they contain. Others, on the contrary, are the result of the ejection of gas from eruptive stars, which ejection is followed by the condensation, in the form of solid grains, of the ejected gases. Whatever the case, the galaxy is full of dust. One of the most interesting regions of the galaxy, its centre, is one of its most massive dust clouds.

Only a few years ago (in the 1950s), 97 per cent of the galactic mass was considered to be in the stars, 3 per cent in the form of gas—and radio astronomy had revealed neutral hydrogen and a few atoms (sodium, potassium), or a few molecules (CN, CH)—and approximately 0.03 per cent in the form of dust. Today it has to be acknowledged that close to one-third of the galactic mass is to be found in the interstellar medium.

The dust and gas are, of course, mixed together in highly variable proportions. But one of the surprising features of this mixture is the fact, discovered a few years ago, that it contains molecular lines of the radical OH, with a wave-length of 18 cm. Since then a very great number of sources of molecular emission have been discovered in millimetric and centimetric radio wave-lengths. Close to fifty molecules are now known, including various isotopic forms of the same molecule. We are thus familiar with not only $C_{12}O_{16}$, but also $C_{13}O_{16}$ or $C_{12}O_{18}$. Study of the interstellar spectrum of ultra-violet has made it possible to detect one of the most important of these molecules, the hydrogen molecule H_2. These discoveries are all the more important in that the molecules thus discovered all belong to the world of carbon chemistry; they are the bricks from which could be formed the amino acids, themselves fundamental elements in organic chemistry. The delicate equilibrium between atoms, molecules and dust grains might well be regarded as one of the most important subjects of astronomical study in the present decade. What is the nature of this equilibrium? How is it maintained or, on the contrary, how does it evolve? Is one to assume that the galaxy came into being cold, in the form more of dust than of gas, or, on the contrary—this is one aspect of the Big Bang hypothesis—should the view be taken that the dust formed through the condensation of gas which was originally very hot at the time that the galaxy was formed? It is conceivable that the analysis of this phenomenon of galactic evolution may yield one of the keys to the evolution of the universe as a whole.

Circumstellar systems, dust and planets

The existence of circumstellar dust is a frequent phenomenon, and it is a noteworthy feature of the galaxy's evolution that such a dense system of fine dust necessarily evolves into an organized system of a small number of solid planets. The discovery of circumstellar clouds, in conjunction with the probable existence of large numbers of planetary systems, undoubtedly lends support to

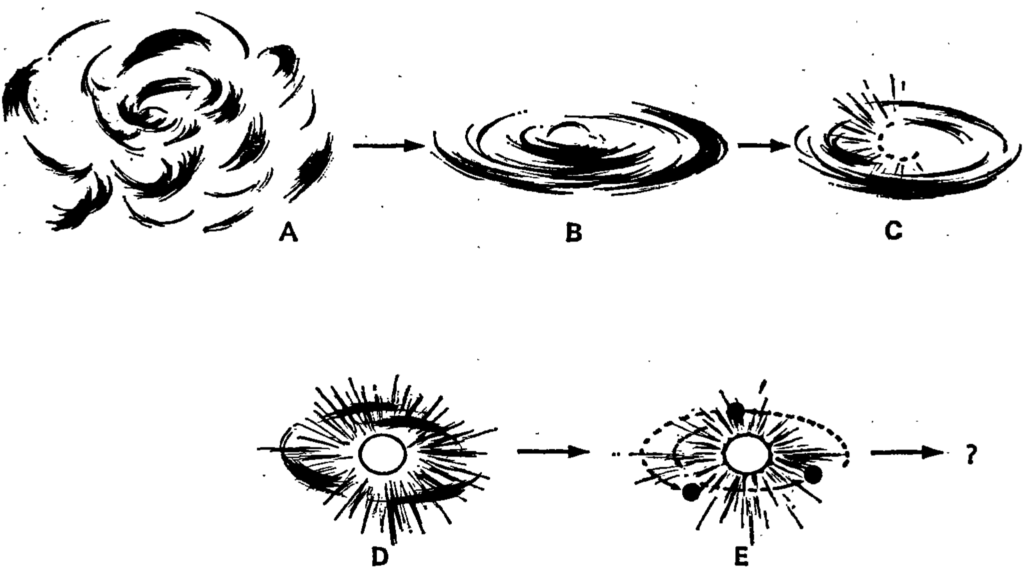


FIG. 15. Diagram of planetary evolution (development of theory formulated by Laplace and Kant).

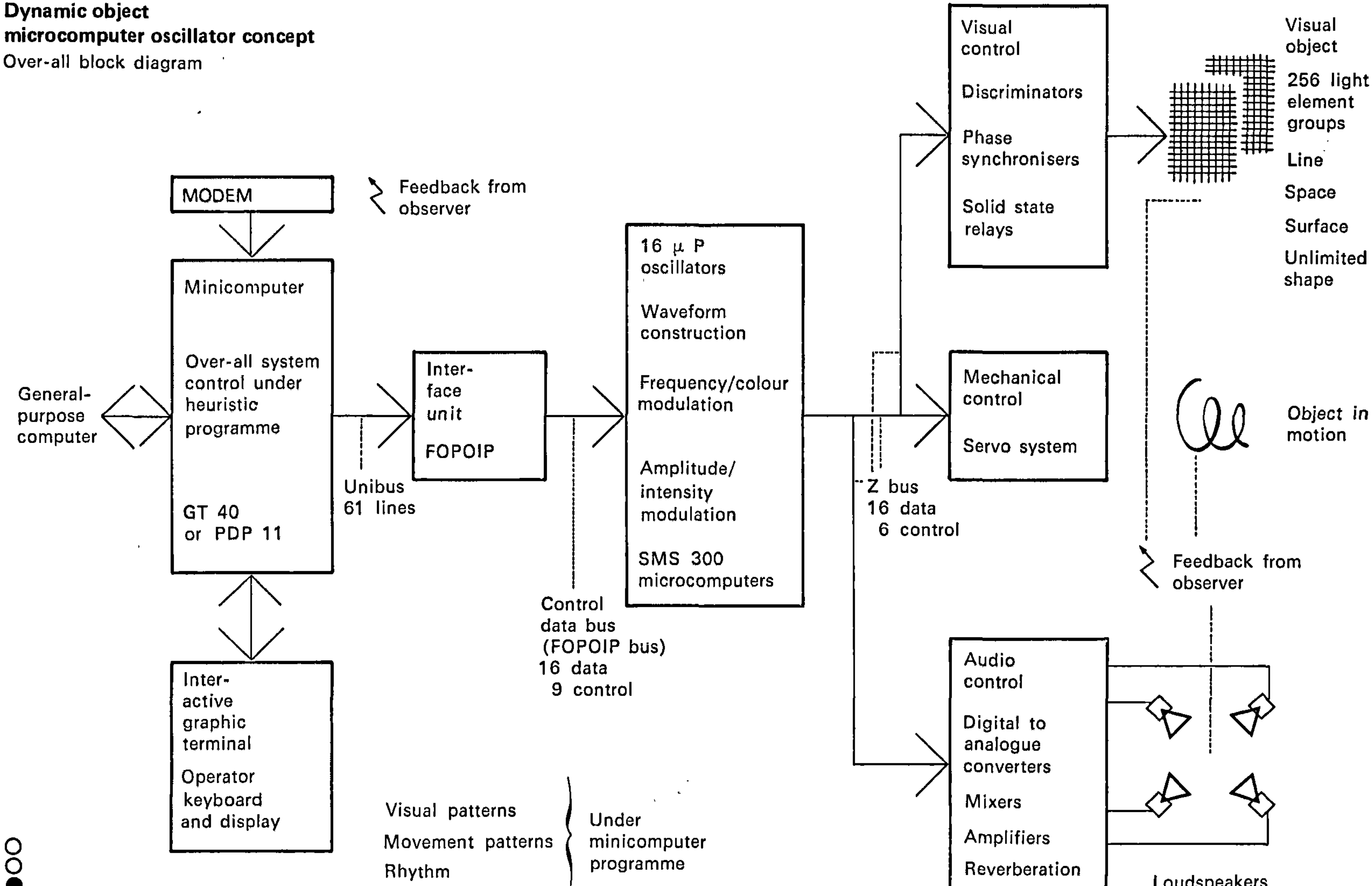
Closely resembling galactic evolution, it merely affects smaller masses. A: a cold and diffuse stellar mass contracts rapidly; B: it has flattened; a star is formed in its dense centre and radiates; C: the star that has formed remains surrounded by a flattened disc of dark dust; D: the disc of dust becomes organized and condensations form planets and satellites in it, at first hazy and separated by a still very dense interplanetary medium; E: the planets have taken shape and the interplanetary medium has been virtually divested of its dust, of which only traces remain. This is the current state of the solar system.

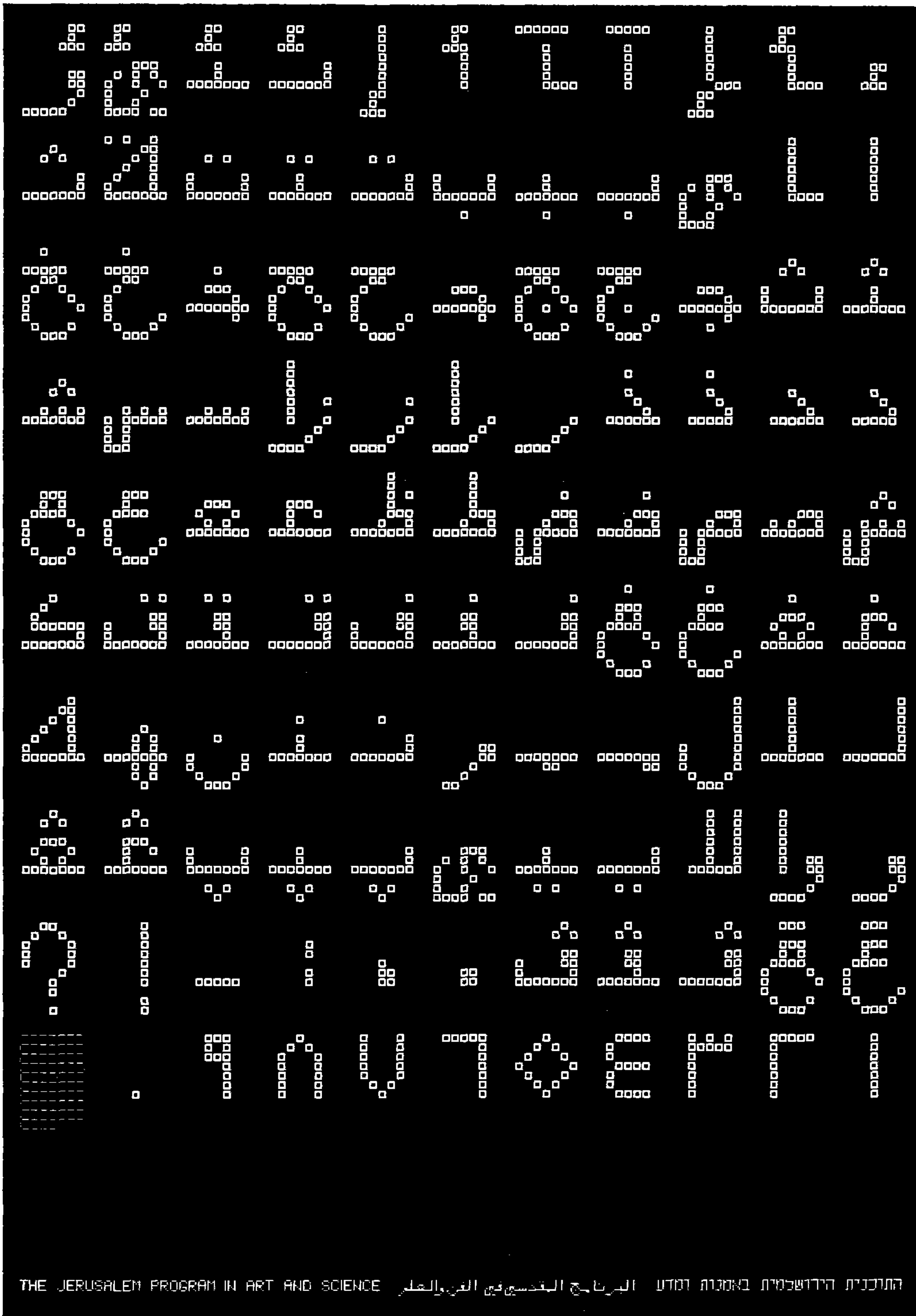
the hypothesis advanced long ago by Laplace (Fig. 15) and recently studied again by von Weizsäcker, and by Kuiper: the planets surrounding a star, such as the sun, did not emerge as the result of some exceptional and catastrophic cataclysm. They formed in the context of a very general phenomenon, which must affect a large proportion of the stars in our galaxy. Millions of solar systems doubtless exist and somewhere, no doubt in many places, are to be found civilizations as advanced, perhaps more so, than our own. But of course this does not mean that it is easy to communicate with them: distances set an enormous barrier in our way; and even a slight diversification of climates and biological evolution may give rise to misunderstandings even more difficult to surmount than those which, under the same climatological conditions, arise between men with different languages and customs, or—the example is even more striking—between a man and a fly, a man and a morning glory or a man and a jelly-fish.

The study of planets was the starting point of astronomy. Their apparent movement across a sky which did not seem to change in any other way led the Babylonians and the Greeks to study their motion in relation to the stars and the sun and to establish theoretical systems governing such motion. Thus were established the systems of Eudoxius, Aristarchus and then Ptolemy; thus was established the Copernican system whose profound implications were grasped by the great Isaac Newton, developing Kepler's ideas. Universal gravitation—slightly modified by Einstein and become relativistic—governs the motions of the planets and their satellites; the laws of gravitation also govern the motions of the thousands of space vehicles, satellites and artificial planets

Dynamic object
microcomputer oscillator concept

Over-all block diagram

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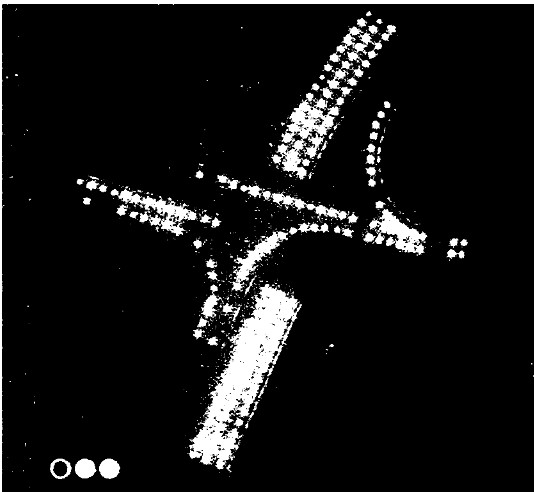

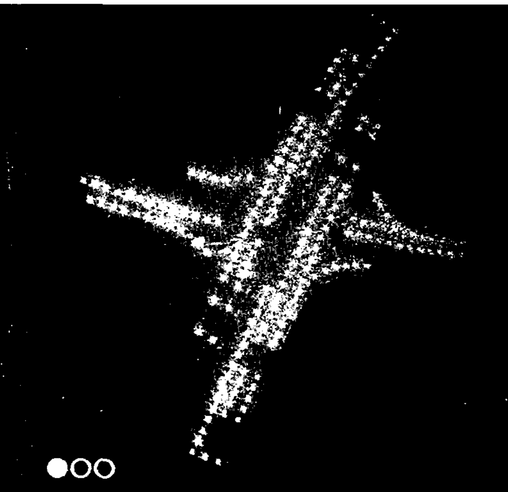

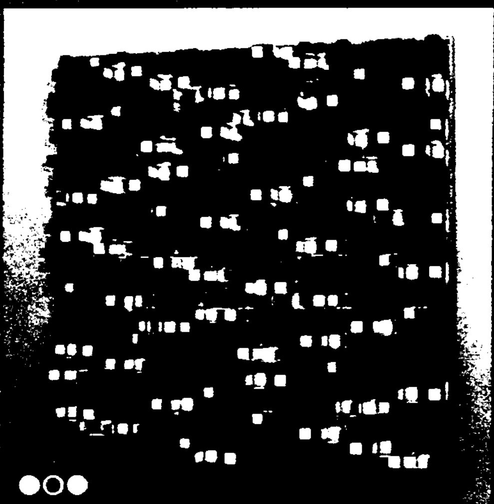

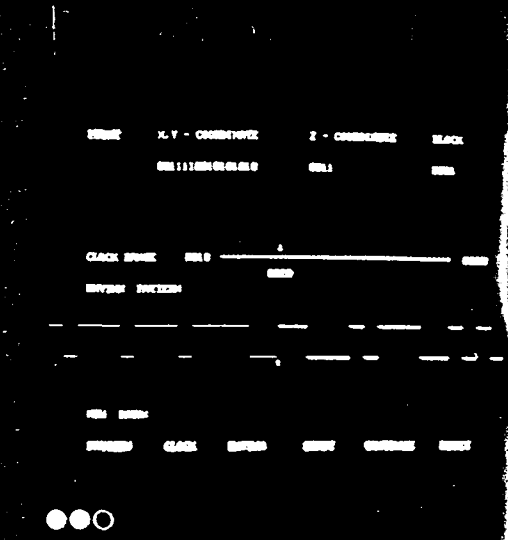

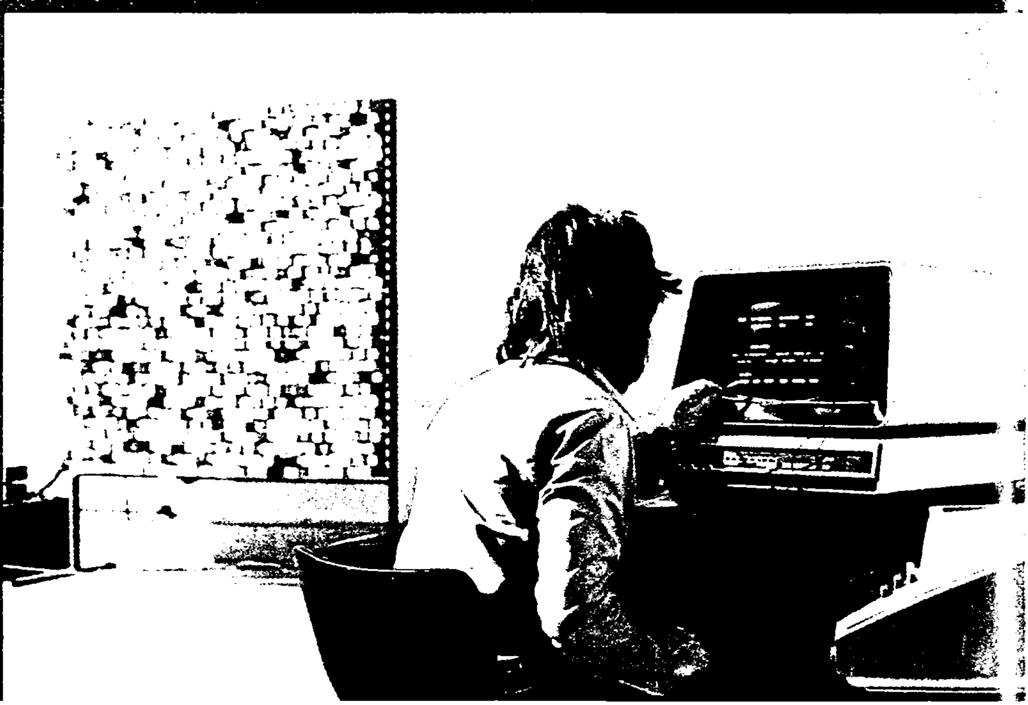

On the boundary between science and art

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The first illustration is that of a dynamic object in space, an original sculpture which can be seen at the Israel Museum, Jerusalem. The visualization of hidden data structures is a problem of some complexity. The sculpture renders visual the dynamic interaction of five patterns in space. It uses 256 red, semiconductor light elements, suspended by the help of tiny, almost invisible wires averaging 2 metres in length. The light elements emit a spectrally narrow band of visible red light, forming interwoven patterns in space. The pattern's appearance, as well as the dimming of pattern orbits, is generated by a computer programme.

○○●

The concept of the microprocessor oscillator in art. It is not the progressively diminishing size (measurable in cubic centimetres), or the power consumption currently measurable in thousandths of a watt, or the increasing speed entering the range of a fraction of a millionth of a second for the basic exchange of information—it is the growth in complexity of the language of microcomputers (the existence of which we become increasingly aware in our everyday lives) that is both necessity and justification for the artist, scientist or research technician who considers the microprocessor as (a) an aid to research and (b) a way of expressing himself to his fellow-men.

The dynamic object (the concept of the microprocessor oscillator) permits an artist to use the microprocessor as part of the 'canvas' which generates light instead of reflecting it, opening immense new possibilities for expression in the fields of sculpture, music and other design, or in science, all of these possessing a rich common denominator in the form of the languages used.

Can we say that the humanization of art is taking place? Energy, communication, locomotion, the discovery of printing, even religious beliefs can be used by alienated societies in an ungenerous way—directed against our fellow-men. But the development of a new language requires such a large number of people involved in the process, contributing to the sharing of the insight evolving between them, that the impact of the malignant influence of alienated social islands is less significant. The establishment of a common denominator would lead to a greater probability of ethical evolution and thus the creation of a new paradigm for society.

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Poster of the first, successfully digitalized Arabic characters for use on computers, using the conventional digital plotter. The original was exhibited at the sixth International Poster Biennale, in Warsaw, and now stands in the Polish Museum. For detailed information concerning the development of the characters, see **impact of science on society,** Vol. 25, No. 1, January–March 1975, p. 90-94.

●○○

Computer-controlled traffic system. This consists of one or more lines of discrete semiconductor light units, fixed in a road's surface, to define moving lanes of traffic. In this new way of directing traffic, 'dynamic' of course means movement, 'static' means stop, the colour code losing its traditional meaning in the red-yellow-green cycle associated with traffic control. Man thus becomes part of the 'dynamic line', moving or halting with it. The system can be used for stop-and-go signals, emergencies, speed regulation, go-slow, change of direction, 'follow me' at airports; to mark roads, intersections, parking areas, pedestrian walks; and to indicate exhibition halls, large buildings, and town plans.

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Computer-controlled traffic system. Another frozen image, a cross roads, of the model of this computer-controlled traffic system.

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Dynamic object: a concept in which impregnable unity is established between the computer system and a work of art. Conceived in 1969, built in Zagreb in 1971 with the co-operation of the Laboratory of Cybernetics, the Rudjer Boskovic Institute, and the Gallery of Modern Arts, it was exhibited at Unesco to mark the Organization's twenty-fifth anniversary. Its audio-visual pattern is repeated after the lapse of 24 days, 6 hours 32 minutes 32 seconds, with a rhythmic change occurring about every 2 seconds. The entire composition can be played, by the computer acting 'alone', in about 7 seconds.

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Dynamic object: conventional computer displaying a medium to monitor and communicate between man and sculpture. The observer adapts his (subjective) needs in regard to speed, rhythm, complexity and choice of pattern orbits.

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Dynamic object: general view. For additional details, see *Leonardo*, Vol. 7, 1974, p. 193.

The areas of interest of the Jerusalem Program in Art and Science are in the fields of ethics, the sociology of art and science, hidden data structures, computer art—especially the concept of 'dynamic object', where the computer system is an immanent part of visual art or music—dynamic lighting of the environment, and some aspects of computer-aided design. Both attractiv eand promising, these topics are also relevant to their respective teaching programmes.

The choice of research concentration (i.e. whatever priority might be considered most significant) is limited first by the general social atmosphere, then by the awareness and readiness for international exchange, by the specialists available, and finally by budgetary considerations. On the basis of experimental work done over a period of years, carried out in many centres, we are confident that Art and Science is a reality both present and future—of a future free from the received ideas of the separation of peoples, an apartness enshrined by differences in language as much as the discreteness of art and science. □

Vladimir Bonacic

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launched by men since a particular day in October 1957.

The science of astronomy, at the time of Newton, was celestial mechanics. The nature of the heavenly bodies was of little importance. They were seen as solid points subject to the forces of gravitation alone. Today the planets are celestial bodies which are explored and visited; they are less and less a matter for the astronomer, behind his telescope, and have become the favourite field of study of the geologist and the geophysician. But celestial mechanics has advanced, like the rest. Since time can be measured more accurately, as can the position of satellites and planets, all disturbances can be analysed. The movement of circumlunar craft has made it possible to discover 'mascons'—regions of the moon whose density is at variance with the mean. The movement of the earth's artificial satellites has made it possible to ascertain more precisely the shape of our planet (just as astrophysical satellites make it possible to study our planet's stratosphere and magnetosphere). Study of the occultations of stars by the lunar disc has made it possible to determine more accurately the movement of the moon, and from this study a surprising fact has come to light: the constant of gravitation seems to vary, each year, by a slight fraction of its value, approximately $7 \times 10^{-11} \pm 3 \times 10^{-11}$; this discovery, curiously, squares with modern measurements of the universe. It is equivalent to saying: 'The universe is expanding, and $H = 55$ km s^{-1} Mpc^{-1}', or else: 'Newton's constant varies by approximately 5×10^{-11} yearly'. It thus emerges that, within the limits of measurement errors, the possibility of interpreting Hubble's law as an indication of something other than expansion cannot be ruled out.

Cosmology: a myth?

We have come full circle. Starting from considerations concerning the universe in the broad sense, we chose to concentrate on the galaxies. Within our galaxy, the study of interstellar and circumstellar media brought us back to the planets. And the mechanics which governs them is subject to the laws which govern the general dynamics of the universe, to such an extent, it is true, that at each turn in astronomical research, problems link up with each other and each phenomenon or each celestial body can only be examined by considering its interactions with the rest. To realize this is as good a way as any of fully grasping the principle of Mach.

We know that, starting from this multifarious universe, tightly interlocking models of the universe have been constructed. What exactly is to be understood by this? At the beginning of this article we mentioned the role of mathematics. For models of the universe are, in the last analysis, tables of functions, deemed to represent quantitatively the properties of our universe as functions of time, its radius, its mean temperature, its density and even fluctuations in these quantities. Every model results from the combination of certain equations which are always valid in all circumstances (by and large, equations of general relativity), in the context of certain metrics of the universe which characterize space-time geometry. The measurement findings (Hubble's constant for instance) then make it possible to solve the equations, and to compute all the parameters. There are very many ways of computing models of the universe which are compatible with that which is observed. But it is also possible to compute that which is observable, but which has not yet been observed; as new observations are made, as that which was observable yesterday becomes that which is observed tomorrow, one cosmological model after another is superseded and done away with. The number of possible new models, more complicated than current models, remains huge. And the cosmologists are giving themselves up to the task with great glee. While solving equations they sometimes no doubt go so far as to forget, in their enthusiasm, the complexity of certain observations; doubtless they also invent new mathematical entities just for the pleasure of it.

Certain entities do in fact result more from very simplistic physical considerations, supplemented by sophisticated mathematical theory, than from a realistic analysis of observations. We shall refer to two highly typical examples.

The physical idea of thermodynamic equilibrium supplemented by the quantum theory advanced by Planck led to the hypothesis of an ideal body, the 'black body', entirely determined by its temperature. However, in order for it to conform with its definition, the black body must be entirely opaque and not lose any radiation; the ideal black body is then, strictly speaking, non-observable. If a hole is pierced in the confines of a black body, it is possible to imagine a small number of photons leaking out of it: consequently, only such a leak could make it possible to measure the energy distribution of the photons contained in the black body, and thus its temperature. Measurement is consequently not possible without disturbing that which is to be measured. Stars are often likened to black bodies: a star is opaque, and the number of photons issuing from it is small in comparison with the number of photons it contains. But the whole of stellar astrophysics shows that what is involved is not a black body and that it is consequently not possible on the basis of the temperature of the surface of a star alone to determine its spectrum. To represent a star by an ideal black body is *a priori* false, but heuristically useful in so far as the deviations measured in relation to the ideal case provide us with a host of valuable information concerning the stellar environment.

Black holes

Another well-known entity (and one which has little in common with the black body despite the sameness of the adjectives) is the 'black hole'. If a sufficiently large mass of matter contracts under the effect of its own forces of gravitation, it may become so dense that it is impossible for matter to leave it—so dense that it is impossible for even a photon to leave it. All the properties of such a black hole can be known by means of calculation.

A concentration of this kind would in fact be evidenced solely by its mass. But can a black hole be observed? It is thought that one has been observed: a double star in Cygnus, one of whose members, though invisible, is an intense source of X-rays eclipsed at regular intervals by the principal component; since this principal star never seems to be eclipsed, it is deduced that the secondary component has a very small radius; as its mass can be calculated, its density can be deduced. It is considerable. The emission of X-rays would be due to gases rushing into the gravitational funnel constituted by the black hole. Such an interpretation is appealing. But why go so far as to postulate a black hole? A white dwarf, a pulsar, are also very dense stars, though not as concentrated as a black hole; light may issue from them, and the arguments in favour of the X-ray source in Cygnus being interpreted as the only known black hole, interesting though they may be, are possibly not the last word on the subject.

Cosmologists thus construct clearly defined entities whose physical existence is possible though scarcely confirmed by observation. In reality, the universe is not in a state of equilibrium, it is not a system of numbers; everything in it evolves, and evolves constantly.

The observer on earth, by virtue of his observation, introduces a disturbance and is moreover sensitive only to that fraction of the universe which is disturbed, which is not in a state of equilibrium. It is not certain that the universe should be transformed into models at any cost; in so doing, we run the risk of reducing it to some idealized universe, of which nothing would in actual fact be observable. An enormous quantity of mass and energy is stored here and there in the immensity of the universe: it is only leaks which are accessible to observation, and what these leaks represent is in fact a deviation from the perfect model.

What then is to be thought of the choice (from among a large number of models) of a particular model—that required by the Big Bang theory—which is consonant with the fundamental observation embodied in Hubble's law? We shall first of all make the point that the universe of those who support the Big Bang theory is a homogeneous, non-hierarchic universe. The observed universe, however, is non-homogeneous and hierarchic, so that the Big Bang theory needs to be radically revised at least, even if it is ultimately possible to retain it in revised form. Those accidents which take the form of abnormal red shifts must be explained by a cause other than expansion: photon fatigue according to some authors, variation in gravitation or other physical constants from one place to another, from one time to another, according to certain other research workers. Why then should not abnormal shifts be accounted for in the same way as normal shifts, that is to say, by reference to Hubble's law?

What will tomorrow's sky be like?

This possible rejection of expansion leads us to postulate a universe which has always existed and to discard the hypothesis of a creation lying outside the sphere of what is observed—a universe which could be far older than the few thousand million years assigned to it by Hubble's law, perhaps an eternal universe. We would then have to accept that this locally variable and fluctuating universe is statistically stable. We would have to accept that in certain places, at certain times, the heavy elements produced in the course of time are destroyed and that hydrogen is reconstituted. Thermodynamics would have to be revised, and in particular its second principle which no doubt would not have the same validity on a large scale as it has on a small scale. What would result would be a universe quite different from that afforded by mathematical cosmologies. It would be a universe in which that which is observed constitutes the only possible basis and the observable, which comes to be observed, in time supplements a partial description without modifying previous provisional descriptions.

We shall therefore refrain from advancing any hypothesis concerning the possibility of observing, beyond the present horizon, a cosmological horizon in keeping with the solutions found to equations of the universe. No observation makes it possible to predict the sky which will be revealed by the more penetrating telescopes of tomorrow. □

Extraterritorial communication: Drake's equation

Astronomer Frank Drake of Cornell University, in his *Intelligent Life in Space* (Macmillan), wrote:

At this very minute, with almost absolute certainty, radio waves sent forth by other intelligent civilizations are falling on the earth. A telescope can be built that, pointed to the right place and tuned to the right frequency, could discover these waves.

Drake's 'almost absolute certainty' is based on an equation he developed for N, the number of technologically advanced extraterrestrial civilizations that are communicating:

$$N = R f_s f_p n_e f_l f_i f_c L.$$

In Drake's equation, R, the average rate of star formation in the galaxy, is equal

to about twenty stars per year.
While f_s, the fraction of stars that are suitable 'suns' for planetary systems, is about 0.1; most stars belong to class *M* (very red, cool stars) and are probably too small, whereas a few, such as *O* and *B* stars, are almost surely too short-lived. The fraction of 'good' stars with planetary systems, f_p, is now thought to be around $\frac{1}{2}$—a value that has helped change scientists' minds about the possibility of extraterrestrial signals. Thirty years ago, f_p was estimated at a pessimistic 10^{-9}.

The mean number of planets suitable for life within such planetary systems, n_e, is probably greater than 1. The value depends on what is considered necessary for life, but even if liquid water is assumed necessary, there are probably several planets per solar system that are neither too hot (like Mercury) nor too cold (like Neptune). Even secondary satellites, such as the large moons of Jupiter and Saturn, may be among the suitable habitats.

Estimates of f_l, the fraction of such planets on which life actually originates, have changed recently, and have given more reason for optimism. Thirty years ago, it was hard to conceive how the organic matter of life could originate. Since then, it has been demonstrated that a mixture of methane, ammonia, water, and hydrogen gases (which are constituents of Jupiter's atmosphere) is transformed by ultra-violet light or electric sparks into a wide variety of amino acids, and precursors of nucleotide bases, sugars and other components of living matter. Some key remaining steps are obscure—it is still not known how replicating substances such as DNA-RNA are synthetized, or how a cell or sex develops. But in an ocean full of organic molecules and with lots of time, these steps do not appear improbable.

The fraction of such planets on which, after the origin of life, some form of intelligence arises—represented by f_i in Drake's equation—is also thought to be high. Evolution doubtless takes place wherever life arises, and intelligence has survival value.

It is intriguing to speculate on the value of f_c, the fraction of such intelligent species that develop the ability and desire to communicate with other civilizations. The intelligent beings might be like porpoises and therefore be unlikely to build radiotelescopes, or they may not have developed writing and therefore cannot accumulate knowledge, or they may have rejected technology and developed a pastoral society, or they may have developed a rigid 1984-type civilization in which such a thing as interstellar communication is discouraged. Nevertheless, few people are so pessimistic as to put the value of f_c below 0.1.

The mean lifetime, *L*, in years, of a communicative civilization might be zero if its members destroy each other before they can communicate, or it may be millions or billions of years if they solve their sociological problems. Because the value of *L* depends on the nature of a civilization that is surely very different from ours, and because even our own society is not clearly understood, this factor is the most uncertain on the right-hand side of Drake's equation.

Since *R* is about 20, and since the product of the next six factors is probably not much below 0.05, *N* may be numerically almost equal to *L*—which means that there may indeed be a large number trying to establish contact.

Robert E. Machol,

'An Ear to the Universe',
IEEE Spectrum, March 1976 (extract).
(Reproduced with permission.)

The molecular universe and the physico-chemical origin of life

Jules Duchesne[1]

From a wide-ranging survey of our knowledge of the physical, chemical and biological origins of life, some important philosophical conclusions may be drawn.

Introduction

One of the most crucial problems of our time is the isolation in which science on the one hand, and philosophy, on the other, have taken refuge. An attempt to reconcile these two aspects of thought which man can only ignore at his peril is undoubtedly a matter of urgency. In this connexion, we are on the shores of a vast ocean of truth, which is still unknown to us, but of which it is imperative to make a preliminary exploration, however incomplete.

Such amazing developments are taking place in science that we are justified in basing great hopes on it as regards the future of mankind. Such hopes are founded on the rapidly emerging unity which is progressively breaking down the formidable, but necessary, scientific barriers of the past.

Thus, under the impact of physics and chemistry, a veritable revolution is occurring in biology and medicine from which as yet unimagined benefits may be expected during the next few decades [1, 2].[2] This increasing coherence of science must also inevitably lead to renewed contact with philosophy; or more precisely, it is the way in which the fundamental and eternal question of the origin of life is approached on the basis of scientific knowledge, that will give substance to such contact.

The molecular factor, from the biological standpoint, will therefore constitute our field of analysis.

The structure of matter

Around 1930, the structure of molecules—even the simplest—was a subject about which very little was known. However, through the application of methods of X-ray and electron diffraction and as a result of the progress in theoretical chemistry, some twenty years later, the great physical chemist Linus Pauling and a number of other distinguished researchers of an adventurous disposition tackled the study of the secondary structure of proteins themselves, thereby passing from substances of low molecular weight to impressive structures composed of thousands of atoms distributed in space in a helicoidal pattern [3]. That was a real change of scale from which important discoveries could clearly be expected and in which the notion of hydrogen bonding (propounded by Latimer and Rodebush in 1920) already played an essential part. In 1953, Watson

1. The author wishes to express his gratitude to his colleagues, Professors Louis Delatte, Paul Ledoux and Jean Serpe, and also to Dr Ivan Ottelet, for some valuable comments.
2. The figures in brackets correspond to the references at the end of the article.

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and Crick, taking as their starting-point the data on X-ray diffraction supplied by Wilkins, discovered that it was precisely this type of linkage which was the key to the structure of nucleic acids, characterized by a double spiral [4].

But probably the most exciting aspect of this is that their genetic function itself is directly related to the remarkable spatial peculiarity resulting from a low energy molecular interaction of some thousands of calories/mole, implying hydrogen atoms linked covalently with nitrogen (N-H) or oxygen (O-H). Hence, the hydrogen bonds are much weaker than the covalent ones, in the region of about 100 kcal/mole, and decidedly stronger than the Van de Waals bonds of about 1 kcal/mole. Furthermore, unlike the latter, they are highly directional. The complementarity of the bases is also governed by this extraordinary peculiarity whose decisive role we shall again observe in what follows.

Although this thought-provoking instance is a really impressive example of the rapid pace of development of contemporary science, we must not lose sight of the fact that is based on a reductionist attitude of mind, since it is by analysing the molecules in question, in isolation from their biological context, that such impressive results have been obtained. In spite of this achievement, it should be realized that this procedure is self-limiting in the same way that, at the macroscopic level, the simple law of perfect gases ceases to apply at high pressures, when the role of environment makes itself felt through increasing molecular interactions. For example, the extraction of DNA, owing precisely to the huge length (in the region of a micron) of the DNA molecule, cannot be done without a risk of fracture, so that although we know that the molecular weight can reach gigantic proportions (possibly in the neighbourhood of a thousand million), nothing is known about its variations according to the evolution of species.

Now, with regard to the increase in genetic information in the case of the higher organisms (since the quantity of molecules of different proteins is ten times greater in man than in the Drosophila) one may expect this order of magnitude will not remain constant but will tend to increase. In so far as this mechanism determines evolution, however, one cannot expect evolution to continue endlessly on account of the threshold beyond which the molecular structure would become unstable owing to its increasing weight [5]. This being so, the process of evolution is likely to slow down to such an extent that it tends to become asymptotic. Consequently, to imagine that beings infinitely superior to man exist somewhere in the universe is, at any rate for the moment, merely the expression of a dream.

Matter itself

Let us now turn briefly to the general problem of matter. Even in the case of physics, which forms the apex of the scientific pyramid, the established laws are only applicable in the experimental field which produced them. For this reason, physics cannot at present, claim, any more than any other science, to have absolute validity. That is why nonrelativist quantum mechanics, the Dirac electron theory, and so on, have successively supplanted each other.

Incidentally, this reminds one immediately of the behaviour of so-called inanimate matter, in which the atomic concept developed by the Greek philosophers 2,500 years ago prevailed (despite bitter disputes) for about two centuries, carried high on the sturdy shoulders of John Dalton.[1] It is at the level of ultra-microscopic particles (of the order of 10^{-13} cm, or 10^5 times smaller than that of the atom) such as the proton and neutron and the hadrons in general, which provoke strong interactions, that insuperable difficulties have recently arisen and have cast serious doubts on the universal validity of this concept since, in the case of extremely high energies in the region of thousands of millions of electron-volts, they can be transformed into each other [6]. This clearly indicates that the notion of 'individual' breaks down at this level and that laws, as yet unknown, predominate that will bring about a reappraisal of basic concepts.

Hence, it is natural to think that if the evolution of matter in its most microscopic state is characterized by a hiatus, the same situation should, *a fortiori*, be found at the other extreme, perhaps through an underlying principle of symmetry at the time the transition towards the living being takes place. An explanatory theory is in full development, thanks to Prigogine and his followers [7-11] who, in order to explain life, have recently postulated dissipative structures in which the essential factor is not so much the individual elements as the co-operation between a vast number of elements. These considerations strongly suggest the likelihood of matter which is both inanimate and living and which would therefore be governed by one single fundamental law which we perceive progressively only in fragmentary form.

The idea of convergence toward the absolute, which is supported by the fact that in the historical development of thought every new theory contains the old one as an approximation, thus remains a justifiable view. For example, we need only remember that Newton's theory of gravitation is the result of general relativity. The notion of unity, to which. I have just referred, is already admirably conveyed in the Old Testament, where it is said that the Lord God formed man of the dust of the ground, and breathed into his nostrils the breath of life, making him a living soul. According to this description, life emerged from inanimate matter but is governed by a more general cosmic law whereby man forms part of a whole in which he is deeply integrated.

A universe with the earth as its centre

It is therefore not surprising, and is in fact perfectly justifiable, that in the Middle Ages, on the authority of Aristotle's *Physics* and Claudius Ptolemy of Alexandria's *Almagest*, there prevailed the notion of a closed, profoundly hierarchical, universe composed of concentric spheres with which the planets were associated and having the earth remaining motionless at the centre [12-14]. But that majestic vision, so peaceful and so secure, could not last. After being subjected to numerous criticisms—amongst which we may cite Nicholas of Cusa's *De Docta Ignorantia* (Learned Ignorance) (1440)—the astronomer

1. cf. his *A New System of Chemical Philosophy*, 1808.

Nicolaus Copernicus (inspired by the teachings of Aristarchus of Samos who lived in the third century B.C.) revived five centuries ago the idea that it was the sun, and not the earth, which occupied the centre of the universe, the earth being only one planet among others. It must not be forgotten that according to Pythagorean tradition fire was the element which was most worthy of occupying a central position in the cosmos [12-14]. There is thus a remarkable contrast between metaphysical ideas in support of cosmogonic theories.

Be that as it may, the loss of the earth's privileged position was no doubt partly offset by a gain; for man, no longer feeling himself concerned with the world, was forced to abandon his traditional anthropocentric outlook. As an illustration of this, we need only recall the case of the Dominican friar Giordano Bruno who, in the direct line of thought of Nicholas of Cusa and Copernicus, dared to assert the existence of living beings on innumerable worlds gravitating around innumerable suns. This opposition—which is so strongly vindicated today—to the prevailing dogmatism of the times led to his being burnt at the stake, as a heretic, in the public square of Rome in 1600.

But this decentralization had a tragic consequence—which was perfectly understood and expressed by the English poet and cleric John Donne, almost a contemporary of Copernicus, and admirably evoked fifty years later by Fontenelle in his *Entretiens sur la Pluralité des Mondes* [15]—namely that science was henceforth to separate man from the universe. Living in a world which precluded all considerations of perfection and harmony, man would no longer feel himself part of a comprehensive whole and he would suffer from this state of affairs which would even affect his subconscious outlook: there is a complete separation between the scale of values and that of facts. Indeed, under the influence of Galileo and Kepler (the latter having demolished the concept of the perfect circular orbit in his work, *Cosmographic Mystery*), physics itself was finally reduced to the study of a host of material points and trajectories.

This scientific revolution of the seventeenth century, by bringing about the destruction of the traditional cosmos, threw the Western world into dramatic disarray. We shall endeavour to show, without dwelling any further on the historical aspects of the question, how contemporary science, by providing insight into the chemical composition of the world, enables us to rediscover a new sense of harmony which is splendidly expressed by life, seen once more in its natural context.

Water and atomic constituents in living beings

Water is by far the most widely diffused substance found in living beings and amounts to some 70 per cent of all matter. Its existence in its liquid state under natural conditions is due, precisely as in the case of DNA, to a minute cause, i.e. the hydrogen bonding. This was demonstrated by Bernal and Fowler in 1933; we can thus see that life is essentially based on that tenuous property [16]. Among the multitude of problems still raised by this astonishing substance at the present time, there is one that perhaps calls for special mention at this point: water exists in several isotopic varieties including heavy water (D_2O), which has the surprising property of being toxic, at any rate as far as mammals are concerned [17]. Although heavy water is fortunately present only to the extent of about 1 molecule for every 6,000 in its pure state even a few drops are enough to kill a rat.

The decisive factor is the increase in mass, through the substitution of deuterium for hydrogen for this causes a reduction of a few hundredth parts of the molecule's residual energy. This produces an increase—admittedly infinitesimal—in the activation energies characterizing chemical reactions, but it is clear that this is sufficient to upset the biochemical kinetics and hence the metabolism. This shows, in the first place, that the addition or subtraction of one neutron can radically affect biological properties and it therefore substantiates the idea that the subatomic level affects more than just inanimate matter. The finding also admirably illustrates the richly suggestive fact that among living beings minor causes often produce great effects. Further examples could of course be given, such as the part played by the photon in vision, olfaction, etc., but this would take us beyond our present field of reference.

It is this situation that is implied in the notion of chance, and it is essential to realize that it is easy enough to use this concept in the belief that it denotes an irreducibility to laws, whereas all it does is to convey the difficulty we experience in connecting minor causes with great effects, owing to the fallacies which inevitably affect the initial conditions. To understand clearly that chance is not the negation of determinism, we need only remember that the Brownian movement of the molecules of a gas can ultimately be expressed in terms of Boyle-Mariotte's extremely simple law relating pressure to volume. Hence, the belief that the evolution of living beings is subject to blind chance, that is to say, to an intrinsic absence of determination, is untenable. Be that as it may, the question arises as to whether the striking toxicity to which we have referred would not be capable in the long run, despite the natural dilution of heavy water, of causing serious disturbances. In other words, we may legitimately ask ourselves whether the phenomenon of senescence might not at least partly be controlled by this factor.

Some experimental findings

To resolve this question it would be necessary to study the changes in the concentration of heavy water in terms of the maximum longevity of the species under consideration [18]. In connexion with this, we have recently demonstrated [19] that remarkable variations in this value could also be explained by an apparently minor effect connected with small changes in the amount of organic free radicals in the brain, whose presence in one gramme of tissue is in the region of 10^{15}. Recently, in the case of animals, some carbon 13 was successfully substituted for carbon 12 up to a ratio of 70 per cent, whereas it normally amounts to about one per cent, and no particular impairment was observed [20, 21]. Admittedly, the variation in mass is particularly low in this case, but that does not necessarily rule out the possibility of subtle effects. We may also expect similar results to those with carbon in the case of oxygen 18 [20, 21], which differs by only two mass units, i.e. by about 6 per cent, from isotope 16 which represents over 99.5 per cent of the whole. But we must again make the same reservations as in the case of C^{13}, thus allowing for the possibility of more subtle effects.

All this brings out another biological truth, namely that life contains within itself the very factors which bring about its end. This does not mean that the end is necessarily pre-ordained. Progress to date, though it still remains in its infancy, seems to indicate that death is merely a universal disease. But it is not to be assumed that heavy water can play only a harmful role. It is perfectly possible that, in the particular case considered here, D_2O might have therapeutic effects in specific concentrations [20, 21].

If we consider the behaviour of living matter at a more complex atomic level, some further remarkable facts emerge [22]. In the human body, for example, hydrogen and oxygen account for about 88.5 per cent of the total number of atoms, 63 per cent and 25.5 per cent respectively. In the case of carbon, nitrogen, phosphorus and sulphur, the respective percentages are 9.5 per cent, 1.4 per cent, 0.2 per cent and 0.05 per cent. These are the six elements which, by themselves, form the molecular structures of all living matter, that is to say, water, proteins (not counting metallo-proteins) and nucleic acids. As regards the twenty-odd remaining constituent elements, many of which are of vital importance, the remarkable fact is that together they represent less than 0.5 per cent. Ten of them are metals appearing in the form of traces, among which we may mention chromium, molybdenum, tin and vanadium (and possibly nickel, the role of which was discovered in 1970). Any diet that does not contain a few microgrammes of these substances causes serious disturbances.

One essential fact must be noted immediately: the four types of atoms which are of predominant importance in life are also the ones which are most abundantly present in the universe [22], namely hydrogen (90 per cent), oxygen (0.057 per cent), nitrogen (0.042 per cent) and carbon (0.021 per cent). As we shall see, sulphur occurs in interstellar space and phosphorus is present in the sun, with a concentration 1,000 times inferior to that of carbon [23]. Thus the raw material of life consists of very ordinary substances. But there is an important process of selection operating at the level of life as the proportion of carbon atoms in living matter, for instance, is 500 times higher than in the universe as a whole, and even in the earth's crust it is very feebly represented (0.2 per cent) and is over 100 times less plentiful than silicon.

At the atomic level [24], deuterium was detected in 1972 in interstellar space at a 92 cm wave-length. With respect to hydrogen, concentration is in the region of 10^{-5}, that is to say, it is practically equivalent to that found in terrestrial water, which is $1.6 \cdot 10^{-4}$. The same holds true when the ratios of carbon, nitrogen and oxygen are compared. These results show that the presence of heavy water in living matter, whatever its purpose may be, was a cosmic necessity.

Molecules in interstellar space

Up to 1940, only a few simple diatomic radicals such as CH, CH^+ and CN which had been identified with optical telescopes were known to exist in interstellar space, and it was hardly possible to imagine the existence of more complex structures owing to the rarefied medium, ionizing radiations and swift elementary particles which, it was thought, rendered this environment absolutely hostile. This was yet another dogma which collapsed when radio astronomy was extended to cover millimetric frequencies by Charles H. Townes, who pioneered microwave spectroscopy.

In 1963, the radical OH was revealed. But later on the discoveries came in quick succession and interstellar space appeared as a wholly unexpected reserve of complex organic molecules [25]. In 1968 and 1969, ammonia (NH_3), water (H_2O) and formaldehyde (H_2CO) were identified; in 1970, it was the turn of carbon monoxide (CO), hydrocyanic acid (HCN), cyanoacetylene (HC_3N), methanol (CH_3OH) and formic acid (CH_2O_2). Then, from 1971 to 1973, the list was extended more rapidly to include methyl cyanide (CH_3CN), carbon oxysulphide (COS), silicon oxide (SiO), methylated derivative of acetylene (CH_3C_2H), formamide (NH_2CHO), acetaldehyde (CH_3CHO), isocyanic acid (HNCO), thioformaldehyde (CSH_2), hydrogen sulphide (H_2S), methanimin (H_2CNH), and sulphur oxide (SO).

The abundance of interstellar matter, especially that concentrated in the spiral arms or central region of the galaxy, is very far from having been fully investigated. Nor is it only through radio exploration that new discoveries will be made; the use of infrared for observation purposes is shortly to be expected. Such an extension will be of the greatest importance, for it will make possible the identification not only of asymmetric molecules (to which radio frequencies are restricted on account of the rules of selection which necessitate an electric dipole moment), but also of symmetric molecules, among which we may expect, for instance, CH_4, C_2H_2, C_2H_4 and CO_2. And there is every indication that amino acids will also turn up.

Interstellar space is not homogeneous, as was previously thought, and the majority of these substances is found in association with particles of dust of the order of one micron in size [26] in very dense clouds some 25 light-years in diameter (1 light-year = 10^{13} km) and with a temperature probably between 4 and 100 K. These dust particles are probably composed of a mixture of graphite, silicate and iron. All the molecules discovered belong to our galaxy. The high intensity of molecular emissions betrays the presence of gas which must be of a relatively high density and must in the case of ammonia for example, reach concentrations of about 10^9 molecules/cm^3, whereas in true interstellar space there is no more than about 1 atom per cm^3.

We are only just beginning to glimpse the way all these substances are formed, but the process suggests a very special type of chemistry related to the extreme conditions in which it takes place. We are thus on the brink of an era in which the development of astrochemistry will constantly stimulate new and productive research in a number of other fields.

Molecules in the planetary atmospheres

Knowledge about the planets and their satellites is based on optical, earth-based telescopes and, more recently, on radiotelescopes, and makes use of the two principal spectral apertures of the earth's atmosphere. The most recent developments are based, however, on the possibility of placing instruments in stable terrestrial orbit or even of sending them either on to other members of the solar system or into the neighbourhood of such. The planets of the solar system are divided into two very distinct categories [27-31]; on the one hand the so-called terrestrial planets, and on the other the large planets. The first group (apart from the moon, which is an earth satellite) comprises, in order of increasing distance from the sun, Mercury, Venus and Mars. In the second group of planets which are much more massive than the first, each of them having an abundant atmosphere, we find successively Jupiter, Saturn, Uranus, Neptune and Pluto.

The moon has been the subject of a large number of recent missions and the varied analyses of samples have, in particular, enabled us to estimate its duration of life at some 4,500 million years, similar to that of the earth. Not only have rocks containing a hydrous iron oxide just been discovered, with an abnormally high water content, but, in addition to carbon which occurs in some soils in the ratio of up to 130 ppm,[1] gases composed of water, CO_2, CH_4, HCN, H_2 and certain hydrides have been identified [32-34]. They probably originate from the solar wind and also perhaps, in the case of water, from comets. There is, however, practically no atmosphere, for gravity is very weak.

The minor planets

Mercury is the smallest of the planets and has a diameter of about 5,000 km,

1. Parts per million.

similar to that of the moon. Its distance from the sun is about 50 million km, whereas the distance of the earth is 150 million km. It is for this reason that the temperature rises to several hundred degrees centigrade on the side exposed to the sun. The temperature on the dark side, on the other hand, falls to approximately —120 C. Its mass is about 10^{-6} times the solar mass; it has a density of 5.7, slightly higher than that of the earth, and its gravity is 2.5 times less than that of the earth. Practically devoid of atmosphere and totally lacking in water, Mercury is now an inhospitable place. It is likely that this was always so owing to its too great proximity to the sun, which must very rapidly have expelled any atmosphere there might originally have been. It has, however, a magnetosphere, i.e. a space where there is a magnetic field governing the movement of the charged particles.

The distance of Venus from the sun, which remains almost constant, is 108 million km. Its dimensions and gravity are comparable to those of the earth. The pressure at the surface is estimated at about 100 atmospheres, and the high temperature, due to a 'hothouse' effect and revealed by microwave radiations, is about 500 C, but that of the cloud layer may drop to 0 C. Here, the density of the atmosphere is very high, 100 times that of the earth, surrounded by a permanent cloud cover, the top of which reaches a height of about 70 km above ground level. Since 1962, Venus has been under observation by Mariner and Venera space probes down to distances of some thousands of miles, and we now know that it is largely composed, throughout its depth, of CO_2, a few hundredth parts of nitrogen, a little O_2, and traces of CO, HCl and HF. Water is believed to occur very high in the atmosphere and it is thought that the clouds containing it in the form of crystals in their upper belt and of droplets in their lower one consist largely of sulphuric acid. The planet's magnetic field is weak compared with that of the earth. However, we now know that it is surrounded by a conducting layer of plasma in which a sufficient magnetic field is induced to exclude the solar wind. Here, too, the nature of the environment seems to rule out any hope of one day discovering life, even of the most primitive type.

Mars, which has already been closely studied by Mariner and by the various Soviet probes of Mars, is a planet situated much farther away from the sun, at an average distance of 218 million km. It receives only about 50 per cent of the light which reaches the earth. Its mass, in the region of 10^{24} kg, is only 0.1 times that of the earth and its density is also much lower, only 3.95 as against 5.52. Its gravity, equal to 0.38, is similar to that of Mercury. Its temperature varies between about 10 C at noon (on the equator) and about —70 C at night. The poles, during the winter, are naturally still colder and may reach temperatures below —100 C. The atmosphere is very thin, the pressure at ground level being equivalent to that found on earth at an altitude of 30 km, and is composed mainly of CO_2, with traces of oxygen and water vapour. There is no nitrogen. The polar ice-caps probably consist of a mixture of solid CO_2 and frozen water, and it would seem that the surface is covered with a hydrated iron oxide (limonite) dust which would explain the dull orange-red colour of what is called the red planet. Mars is thus likely to be the only planet containing enough water to produce this effect.

Carl Sagan has put forward the theory that if the atmosphere on Mars is condensed in the polar ice-caps, it would be capable of becoming vapourized periodically and so producing, over the entire surface, abundant water and a pressure about 100 times greater, that is to say, comparable with that of the earth. Furthermore, the existence of a dozen or so canals, apparently formed by a liquid, presumably water, would seem to indicate that at one time Mars had a very different climate from its present one. An important point to note is that an ozone layer similar to that surrounding the earth does not appear to exist now, which means that the planet's surface is perpetually subjected to ultra-violet radiation from the sun. Nor has a magnetic field of any significance been detected, though it is likely that a similar situation to that found on Venus exists. Bearing in mind life's extraordinary capacity for adaptation and resistance to hostile conditions, as the developments in cryobiology so admirably demonstrate, we may conclude that conditions are such as not to rule out *a priori* the existence of a rudimentary form of life remaining latent during adverse periods and reviving when circumstances are more propitious possibly in micro-environments which are more in conformity with fundamental needs. (We refer here only to the ability to survive.) However, micro-organisms might have made their appearance at the time when the original atmospheric conditions prevailed, probably composed of ammonia, methane and other reducing gases, and then later have evolved towards a form of biochemistry similar to that of plants, that is to say, based on the action of chlorophyll, and therefore on the available CO_2.

The major planets

The situation in the case of the major planets is radically different. Jupiter, which is for the most part a liquid planet, is too hot to become solidified, despite its enormous internal pressure of some millions of atmospheres. Its mass is 300 times that of the earth, but its density is remarkably low—only 1.33 that of water, or 0.24 that of our planet. Its average distance from the sun is less than five times the distance between the sun and the earth [27-31]. In the transition belt towards the liquid state, about 1,000 km below the upper limit of the atmosphere, the temperature is around 2,000 C. But 3,000 km lower down it reaches 5,500 C and the pressure rises to 90,000 atmospheres, according to the results obtained by Pioneer 10. The atmosphere is almost entirely composed of hydrogen and helium, and all the other elements combined only represent 1 per cent—these proportions being similar to those of the elements which occur in the sun. The atmosphere is hidden by very cold clouds which form its apex and contain ammonia crystals below which reddish brown regions occur, probably composed of crystals of ammonium hydrosulphide. Still lower down, there is frozen water and, probably, droplets of liquid water containing ammonia in solution. Lightning, thunderstorms and other meteorological events can take place, for Jupiter possesses a vast amount of energy and an extremely turbulent atmosphere. The outer atmosphere above the clouds contains a mixture of ammonia and methane. Higher still, there appears to be a layer of droplets and hydrocarbons such as ethane and acetylene.

All this gives grounds for thinking that a region favourable to the development of prebiotic systems could exist. Recent radioastronomy observations have revealed the existence of a gigantic radiation belt (similar to the Van Allen belts in the case of the earth), with a diameter three and a half times that of the planet, and which is situated outside it. This indicates the existence of a strong magnetic field.

Saturn's mass is ninety-five times that of the earth, while its extraordinary low density is only 0.7. Gravity is practically the same as on earth. Saturn's average distance from the sun is twice that of Jupiter. Observations have shown that the qualitative composition of the atmosphere strongly resembles that of Jupiter, although in Saturn's case gravitation is not sufficient to exert any strong pressure on the component gases. Infra-red radiation measurements show the temperature to be lower than that of Jupiter. Saturn's concentric rings in the middle of which it revolves are very thin and have a diameter of 270×10^3 km, i.e. over twice the diameter of the planet itself. Their origin remains obscure and little is known about their composition. If a magnetic field exists, nothing has yet been discovered as to its effects.

The mass and gravity of Uranus are, respectively, 14.5 and 0.9 times those of the earth, its density being 1.6 times that of water. Its average distance from the sun is about twice that of Saturn. There are probably large quantities of hydrogen and helium in the atmosphere in which spectrum analysis has revealed large quantities of methane, and it is also thought likely to contain a little O_2 and SO_2. The ammonia is probably entirely condensed owing to the very low temperature, which must be in the region of —150 C.

Neptune is thirty times farther from the sun than the earth. Its mass is 17.6 times that of the earth, its density with respect to water is 2.2, and its gravity 1.41. Spectroscopic investigation shows that the atmosphere of Neptune, like that of Uranus, contains hydrogen and considerable quantities of methane, the methane being in solid state owing to a temperature of about —200 C. Pluto, the outermost planet, is, however, at a scarcely greater average distance from the sun than Neptune. Its mass can hardly be less than that of the earth. Nothing is known of the planet's atmosphere or internal structure. We shall not concern ourselves here with the satellites revolving round the major planets as that would not contribute anything further to the matter in hand.

The salient fact brought out by this brief survey is that the atmospheres of the major planets are an extraordinary reflection of interstellar space, since they contain hydrogen (of which there is no trace on Mars or Venus), helium, water, methane and ammonia. We cannot, of course, come to any conclusion at present regarding the possibility of there being actual life at this level, but we must admit—as the experiments we shall go on to describe suggest—that their atmosphere is singularly favourable to the formation of organic molecules which are the basis of living matter. If the terrestrial planets do not possess these striking characteristics it is simply because, as in the case of the earth itself, it is no longer a question of a primitive atmosphere whose preservation made very low temperatures and high gravitation constants necessary, but of a secondary atmosphere.

Carbonaceous meteorites

Meteorites, which fall at random on the earth, have a very long history behind them, admirably described by Bigot de Morogues in his work *La Chute des Pierres* (1812). These celestial bodies have a life expectancy comparable to that of the earth or the moon. They are divided into two major categories: iron meteorites, mainly composed of iron and nickel, and stony meteorites of which there are thirty or so examples characterized by an extraordinarily high carbon content (thus Orgueil contains some 5 per cent of carbon and 7 per cent of organic matter). That is why such meteorites are known as carbonaceous meteorites. These meteorites, which together weigh a total of some 150 kg, have become of great scientific interest because of their wealth of extraterrestrial organic molecules [35–38]. As examples we may cite: Alais (6 kg) and Orgueil (10 kg), which fell in France in 1806 and 1864 respectively; Cold Bokkeveld (3 kg) in South Africa (1838), Migey (8 kg) in the Union of Soviet Socialist Republics (1889), Mokoia (45 kg) in New Zealand (1908), and Murray (7 kg) in the United States of America (1950). The basic substratum of these bodies consists of olivine and serpentine, substances formed by orthosilicates of magnesium, relatively deficient in silica, the latter being hydrated. It was in 1806 that the celebrated physicist J. B. Biot finally established, at the behest of the Institut de France, that meteorites—contrary to the views of others such as Lavoisier, who held them to be of volcanic origin—had in fact an extraterrestrial source.

From then on, reassured on this important point, great chemists (Berzelius, in 1834; Wöhler, Cloëz and Berthelot, in 1858, 1864, and 1868, respectively) became interested in a problem that was now correctly formulated, and succeeded with the simple analytical means of the time in demonstrating the existence of hydrocarbons and substances similar to coal and lignite in both Cold Bokkeveld and Orgueil. However, Wöhler (who had already, in 1830, succeeded in synthesizing urea, thus demonstrating that natural substances were not beyond the reach of science and could be produced with the aid of its methods) defended the thesis (another instance of mind-conditioning through tradition) that the organic molecules in question were the products of degradation of some pre-existing form of life.

It was not until nearly a century later, with G. Mueller in 1953, that discussion of the problem was resumed and intensive research undertaken with the application of sophisticated techniques of analysis, including chromatography, optical spectroscopy, the methods of nuclear and paramagnetic resonance, and mass spectrometry.

Fairly complex molecules

A large number of carbonaceous meteorites were investigated by brilliant researchers such as Calvin, Urey, Kaplan, Anders, Claus and Nagy and an impressive body of findings was compiled. Thus, normal unbranched paraffins were identified, containing a large number of carbon atoms (perhaps as many as twenty-three), aromatic acids, phenols, long-chain fatty acids, sugars such as mannose and glucose, isoprenoid hydrocarbons such as pristane ($C_{19}H_{40}$) and phytane ($C_{20}H_{42}$) corresponding to the phytic chain of chlorophyll, and lastly, amino acids, traces of nucleic bases (adenine, guanine, cytosine) and even porphyrins, especially in Orgueil, Migey, Cold Bokkeveld, Murray and Mokoia. The mere fact that the isoprenoids were identified raised some troublesome problems, for attempts at laboratory synthesis that had initially failed gave the impression that they were of biological origin.

But the findings about which most ink has been spilt are no doubt those concerning amino acids, whose origin appeared to be a matter of doubt. In 1958, we put forward certain arguments based on the homogeneous nature of the distribution of the free organic radicals that we had identified in Alais, Cold Bokkeveld, Nogoya and Migey in favour of the indigenous character of those substances. Moreover the methods used required only a few milligrams of the substances and did not entail any manipulation likely to introduce impurities. Nor was the structure in any way affected, contrary to what happens with other methods. However, eleven years later, a timely gift fell from the heavens to enable the difficulties to be directly and definitively resolved.

I refer to the meteorite Murchison (Australia) [39, 40] on the one hand, with 2 per cent of carbon and whose largest fragment weighed 2.5 kg, and on the other, to the meteorite Allende (New Mexico) [41], with 0.3 per cent of carbon, the analysis of which supplied the knowledge that was wanted. In the latter case, about 5 tonnes were collected within five months after its fall, including fragments weighing up to 110 kg.

Thanks to the experience already gained and to the fact that these meteorites were quickly subjected to analysis by selecting the less fissured fragments, it was possible to eliminate the serious disadvantages inherent in samples that have lain for a long time in museums. Thus, in the case of Murchison, a series of amino acids were identified, several of which are normally present in living cells, such as glycine and analine, which were by far the most abundant, valine, proline and glutamic acid, representing a concentration of 15 $\mu g/g$ of matter.

A key observation

One decisive observation was made: the laevorotatory and dextrorotatory forms of these substances are present in approximately equal quantities. It is all the harder to assume that they are a racemization of amino acids of biogenic origin in that 2-methylalanine and sarcosine were also found to be present, and these do not usually belong to proteins. This important discovery was regarded as proof that the organic molecules are of abiogenic origin and therefore the result of an extraterrestrial abiotic synthesis.

Even though Allende does not contain any amino acids, the major discovery consisted in identifying, for the first time in a meteorite, formaldehyde in the form of its polymer, paraformaldehyde, with a concentration of some three ppm. Various suggestions have been made as to the possible formative mechanism of this compound, but the essential point is that it also belongs to interstellar space.

Just recently, research has been resumed on the meteorite Orgueil [42], considered a classic case. Glycine, alanine and valine were also found, as well as aspartic acid. Six additional amino acids, not belonging to the proteins, were encountered and, once again, in racemic form. There could therefore be no possibility of contamination due to earth sediments.

Comets

Comets are bodies of very small mass, hardly exceeding 10^{18} kg, or about 10^{-6} times that of the earth. At a distance of less than one and a half times the distance separating the earth from the sun, it can be seen that they have a head in the midst of which may be discerned, on the one hand, a nucleus which is several kilometers in diameter and with a gaseous cloud around it resembling a mane and, on the other, a tail, on the side away from the sun, which may stretch for millions of kilometres. The mane itself, under certain conditions, can reach 10^5 km in size.

The nucleus from which the luminous gases evidently emerge which, on approaching the sun, are distributed in the mane and tail, seems to be composed of solidified gases such as H_2O, CO_2, CH_4, NH_3, HCN, C_2H_2 and C_2H_4. It is therefore in the nature of things that the principal emissions from the heads and tails of comets include the following molecules and radicals, whose presence depends on the distance from the sun: C_2, C_3, CH, CH^+, CN, NH, OH, N_2^+, NH_2, CO^+, CO_2^+ [27–31, 43, 44]. As confirmation of the already well founded assumptions with regard to the composition of the nucleus, ionized water (H_2O^+) was recently discovered in the tail of the comet Kohoutek (observed on 7 March 1973, close to the orbit of Jupiter), thus providing the first proven example of the presence of water in celestial bodies [45]. Methyl-cyanide (CH_3CH) and hydrocyanic acid were also detected.

One cannot therefore fail to be impressed by the fact that this composition admirably reflects molecular interstellar space.

Origin of carbonaceous meteorites and comets

Our purpose is not to discuss current theories relating to the origin of these bodies. We cannot, however, pass over the interesting suggestion that carbonaceous meteorites originate from periodic comets, or even perhaps, according to recent observations, in the case of some such meteorites from the asteroid belt between Mars and Jupiter [43, 44]. The essential point is the certainty that these two groups are of extraterrestrial origin and that, hence, their ultimate source lies not in interstellar space but in the solar nebula. It may be assumed, therefore, that the molecules which occur in them pre-existed all those in the latter.

We must, however, beware of over-hasty extrapolation, for it is always possible that the most complex among them are the result of a subsequent synthesis, during the actual life of those bodies. Before long, moreover, it will be possible to go to those comets which remain within range of the earth and bring back samples with a view to a far more searching analysis.

Molecular palaeontology

More intensive research on the origin of life has, during the past decade, injected new life into palaeontology. The originality of the investigations carried out lies in their being directly linked with one another in a broad context in which geology and chronology play a decisive part.

The new avenues of approach to palaeobiology are specifically due to advances in our knowledge concerning the age of Precambrian systems of sedimentary rocks. Other crucial factors have been the use of the electron microscope for observing minute objects of biological origin and the development of methods of analysis. It has been possible, in regions far removed from one another such as Africa, Australia and Canada, to identify micro-organisms (bacteria and algae) whose structure has been preserved and which, more particularly in southern Africa, occur in rocks whose age is known to be 3,100 million years [46, 47].

Authentic molecular fossils have also been discovered [46, 47], which are sufficiently stable to have survived for some 3,000 million years, for example, saturated hydrocarbons, especially pristane and phytane, which have also been found in carbonaceous meteorites.

Physico-chemical origin of life, synthesis of amino acids

It is striking to note that organic matter occurs in a wide variety of circumstances throughout the universe, so that the universe may today be considered as being organocentric. But the essential point at issue is to know whether the relationship between the simple molecules which have been observed and the complex molecules such as amino acids and nucleic bases which have been identified in some heavenly bodies, is a true cause-and-effect relationship, or whether it is merely a question of parallelism. This is naturally the key to all future development. We see how decisive its importance is when we call to mind Charles Darwin's extraordinary intuition. Darwin, who knew nothing of the prodigious discoveries just referred to, envisaged the possibility of there being a continuity in evolutionary events leading back towards the past, by propounding a prebiotic molecular history, at any rate on the earth's surface. He claimed that protein compounds could have been formed in a small pond, provided that organic compounds, ammonia and microcosmic salt were dissolved in it and the pool was subjected to the action of light, heat and electricity. This thesis, clearly formulated in 1871, was subsequently taken further in 1910 by the chemist Giglio Tos in his work, *The Problems of Life*. It is necessary to assume that the terrestrial environment of the past was totally different from that of today, and that the first biomolecules made their appearance under certain highly specific initial circumstances.

To adopt this notion of the continuity of natural phenomena, leading from the molecule to the level of life, is undoubtedly a bold step as it implies a fraternity embracing both animate and inanimate matter—a fraternity the possibility of which had been demonstrated at least in part by Wöhler's discoveries. We are thus oddly brought back to the ancient concept of spontaneous generation, denied by the discoveries of Pasteur which were endorsed by Claude Bernard. However, after having demonstrated in 1860 that life never occurred in a sterile environment, Pasteur made certain reservations ome years later, specifying thats the demonstration in question was only valid within its experimental context.

It is to the insight of T. H. Huxley, J. Tyndall and the Belgian Leo Errera that we owe the subsequent realization that all that was necessary perhaps was to invoke the notion of time, which was available on a cosmic scale, rather than to postulate some instantaneous transformation, to account for the phenomenon in question. As early as 1924, within the context of this promising concept, a first precise model was put forward by the biologist A. I. Oparin, followed up, in 1928, by an independent but similar suggestion made by the geneticist J. B. S. Haldane, and later on by J. D. Bernal. A further contribution to the investigation of the problem was made by A. Dauvillier in 1938.

According to the first three authors [48, 49], when the earth's crust was formed, the earth was surrounded not by an oxidizing atmosphere, as it is today, but by a primitive reducing atmosphere composed of H_2, CH_4, NH_3 and H_2O, whereas Dauvillier [50] held that there had been carbonic gas but not free hydrogen or methane.

The role of the atmosphere

It was under the influence of electric discharges and of ultra-violet solar radiation that the atmosphere in question became the cradle for the formation of organic molecules, which could only have avoided subsequent destruction by scattering, not only in the direction of the oceans but also towards the lagoons and coastal fringes, where they became established. The notion of a reducing atmosphere received additional support from the arguments developed by Harold Urey in 1952 and based on an analysis of the thermodynamic properties of the gases in a cloud of cosmic dust from which the solar system was formed [48, 49]. The soundness of that intuition was fully borne out by what was subsequently learnt about the organic composition of interstellar space, which has the remarkable property of being a reducing agent, as had been imagined. Then, in 1953, the investigations of Stanley Miller, one of Urey's disciples, working on a so-called simulated reducing atmosphere composed of hydrogen, methane and ammonia, corresponding to respective pressures of 10 and 20 cm of mercury and activated over a period of one week by electric discharges of 60,000 V—thereby imitating the effects of lightning—proved that, under such conditions, what was obtained was chiefly the formation of four amino acids: glycine, alanine, aspartic acid and glutamic acid. These are the simplest, the most prevalent in proteins and with a higher yield, since more than 2 per cent of the carbon introduced in the form of methane was transformed into glycine. But there were many other compounds besides those, including formic acid (in great abundance) and hydrocyanic acid [48, 49, 51, 52].

These initial investigations triggered off research on a vast scale, which is far from having run its course and which has brought about changes both in the energy resources involved and in the environment as such. Thus, taking the primitive atmosphere as the starting-point, i.e. by maintaining the strictly indispensable reducing character of the environment, most of the amino acids forming proteins have been finally synthesized, by making use either of electrons or of X-rays or gamma rays which are present in solar radiations [53, 54]. It is thus established that it was possible for the amino acids common to all forms of life on earth to accumulate in large quantities during the prebiotic period.

The extraordinary finding which emerges from these experiments is that among the host of possible reactions leading to stable products, the prevailing tendency is precisely for constituent units of proteins to be formed, provided the initial mixture is not an oxidizing one. Moreover, it is extremely interesting to note that thermal syntheses give rise to a distribution of amino acids in which there is a clear predominance of a great variety of natural forms, even as compared with the results obtained through electric discharges [55].

Synthesis of the constituents of nucleic acids and biopolymers

The exciting thing is that in choosing a different molecular mixture, but one whose constituents such as formaldehyde, hydrocyanic acid and cyanacetylene (H_2CO, HCN, HC_3N) occur not only in interstellar space but also in the meteorite Allende and the comet Kohoutek, we have been able to observe the formation, under the action of various exogenous sources, of fatty acids, sugars (including desoxyribose of DNA), purine (adenine) and pyrimidines (uracil and cytosine) [27–31]. It is worth remembering that several of the above substances, which are the bases of nucleic acids, have even been discovered in the meteorites Orgueil, Murray and Mokoya [35–38]. As protons are present both in the solar wind and in the planetary radiation belts, where they reach high energy values, they have also been taken into consideration. Varied mixtures containing, in particular, methane, ammonia, water and sulphuretted hydrogen have been studied.

On this basis, in addition to organic substances similar to those mentioned above and sulphuretted derivatives, a polymeric sulphyr containing predominantly the compound S_8, of a yellow colour, was detected, which might explain the existence of the coloured strata observable on Jupiter [56]. After that, research was taken still further. The work of Fox and his associates made it possible to polymerize by pyrocondensation, at about 100 C, eighteen amino acids common to proteins, in polypeptide chains, with molecular weights of the order of 15,000, known as proteinic substances [57]. The compounds obtained are even highly selected, and there is of course a problem of steric interactions which needs to be thoroughly investigated.

In addition, these thermal polymers display nutritive properties and also, sometimes, an enzymatic type of activity. This behaviour provides an additional argument in favour of the view held by a large number of biologists to the effect that it is not necessary to postulate priority in time in the case of nucleic acids. It is worth recalling a domain in which the radio-activity of the ground has been found to be a singularly effective source of energy. The relatively high concentration of free organic radicals of about 10^{15} centres per gramme (detected in lignites by means of paramagnetic electronic resonance) can be explained only by the action of alpha particles (emanating from associated uranium) over a period of some 10 million years [58].

As, moreover, it is well known that massive doses of gamma radiation on a solid such as carbonate of ammonia lead to the formation of formic acid, glycine, and possibly alanine, it would not be at all surprising if not merely the atmosphere but also *terra firma* itself served as nature's starting-point in enriching the primeval sea by the addition of organic molecules.

Transformation and syntheses

Schramm, following up the work of Ponnaperuma and Sagan, succeeded (at 60 C) in transforming nucleotides into polynucleotides, with molecular weights of the order of 10,000, symbolizing in their turn DNA [59, 60]. Admittedly, the synthesis of nucleotides presupposed the use of polyphosphoric acid, the existence of which as a primitive terrestrial agent is not self-evident. The fact that this substance is itself a result of the heating of phosphoric acid salts, however, is particularly reassuring. As for the phosphorus element—which has not so far been detected in interstellar space—it is found in the sun [23] and in meteorites such as Orgueil, Ivuna and Murray, in quantities equal to 1 per cent of the carbon content [35–38].

These experimental results, when placed alongside our present knowledge of the organic state of the universe, make it possible to resolve the ambiguity which remained when it was stated that the presence of biomolecules in celestial bodies was the result not of chance but of a closely linked sequence of physico-chemical events starting at the most primitive stage, namely hydrogen, methane, ammonia, hydrocyanic acid, formaldehyde, etc., which occur throughout the universe.

Another experimental approach is connected with the study *in vitro* of replication processes. In this connexion, it should be noted that Kornberg and his associates [61] first successfully synthesized DNA molecules in a test tube reflecting the structure of the original matrix. Subsequently, in about 1970, by making use of a virus—an agent that may be regarded as a borderline case of life—the same team was able to produce, in two stages, an infectious DNA, thereby building up a little 'chromosome'. It must not be thought, however, that such a system is a live one, for it cannot fashion the basic elements, i.e. the mononucleotides, on which it feeds, nor multiply the polymerase macromolecules which cause it to proliferate. But it can be affirmed that, despite the remarkable progress of physico-chemistry in the sphere of synthesized macromolecules, it has not been possible to achieve anything comparable.

We can imagine, therefore, that these might well be systems constituting a kind of transition between the inanimate and the living. The special and unique property of the latter is its capacity to reproduce itself in such a way that its variations are incorporated in its replications.

Origin of the cell

As the probable mechanisms whereby the molecules forming the biochemical basis of life became more clearly understood, the time came to embark on a second and even more adventurous phase at the end of which the processes governing the formation of primeval organisms themselves might be understood [62]. Up to now, some striking research in this direction has been undertaken by Oparin, Fox and others. In the initial stage, use was made of coacervates, which form colloidal droplets capable of concentrating amino acid and nucleotide polymers in a homogeneous and highly diluted medium. According to Bernal, polymerization takes place on the surface of substrates, which are thus able to play the part of catalysts. This is why numerous investigations have been concerned with the behaviour of clays and other substances. However, in this case, the experiments which have been carried out by means of current biomolecules extracted from plants or animals can only be regarded as being a very important starting-point for subsequent, doubtless more fruitful, research.

Such is the case with synthetic proteinoids, which are better adapted to actual conditions and which possess the curious

Origin of the optical activity of biomolecules

Numerous organic substances can exist in two closely similar forms; their molecules are composed of the same atoms, but these are differently arranged in space, so that each form is a mirror image of the other. It is a question of optical antipodes which deflect the polarization plane of light in the opposite direction [27–31, 58]. Chemical synthesis invariably gives an equal mixture of the two dissymetric forms.

At the level of biochemical processes, however, a peculiarity is once again observable, for only one of the two isomers can be detected, in either the right-hand form or the left-hand form. The latter form is precisely the one which characterizes the amino acids entering into the composition of terrestrial proteins. According to Dauvillier and Bernal, the first asymmetric synthesis of a given macromolecule occurred from a single, optically active molecular mould. As quartz is the only common mineral which is asymmetric in structure, it might well be the adsorption locus for organic matter in evolution. Now, it is precisely on the surface of such crystals that a certain number of asymmetric syntheses, in solution and at an ordinary temperature, have been achieved. On this basis, it is therefore reasonable to suppose that, under natural conditions, active compounds of high molecular weights could perfectly well have been formed. As there seems to be no reason to suppose a predominance of crystals of a single type, one should take the view that the choice is due to chance, that the process, once set in motion, remained identical, which is Eyring's point of view.

A second mechanism cannot be ruled out for, as Doty has shown, during the actual process of polymerization the left-hand form takes shape even more rapidly in certain cases than the racemic form.

A final although more speculative hypothesis consists in relating this phenomenon not only to purely physico-chemical processes, but also, in a decisive way, with weak interactions which do not respect the non-preservation of parity. If this is so, the left amino acids should predominate throughout the universe; but observations made of carbonaceous meteorites make such an assumption altogether obsolete, since only racemics are found in them.

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property of coming together on contact with water to form microspheres capable of growing and reproducing themselves by spontaneous division. These microspheres are of the same pattern and the same size, and they tend to combine in the same way as certain bacteria, so much so that they can sometimes be mistaken for them. In spite of these extraordinary and fully justified efforts, it must be admitted that we still have a long way to go before it becomes possible to reproduce a living cell *ab ovo*, particularly as the idea of a symbiotic mechanism, implying the notion of elementary primeval units which are already living, although less complex than the cell, can certainly not be ruled out, and is even highly attractive.

We must face the fact that the whole evolution of events that we have analysed fully justifies the heterotrophic theory (use of preformed organic substances), which itself presupposes an anoxic environment. The only way of meeting this need lies in the process of fermentation whereby organisms obtain the necessary energy for living, growing and reproducing themselves. By doing so, living beings consume their own reserves, and this can lead to their individual extinction. On the other hand, as a result of the photodissociation of water vapour, the atmosphere tends to become oxidizing.

The authotrophic state and photosynthesis

In order to deal with these obstacles coinciding with the appearance of a layer of ozone which, since it made the atmosphere opaque at wave-lengths below 3,000 A, must have deprived any organic molecules which subsisted of one of the principal sources of energy, it was necessary for the autotrophic state (inorganic environment) to develop and gradually take precedence over heterotrophism. The situation was fortunately saved by the undoubted presence of CO_2, due to volcanic action and given off when fermentation took place, since it was CO_2 that enabled life to continue, through the operation of the process of photosynthesis.

The inexhaustible source of energy represented by the sun enabled the new process to construct its own organic molecules itself and, remarkably enough, with a far higher energy output than in the case of the preceding process [63]. But as photosynthesis generates oxygen, from then on, a third stage based on cellular respiration became possible. Here, the combustion of 180 grammes of sugar produces about 700,000 calories, whereas the same phenomenon involving the fermentation by yeast, produces only 20,000. This makes us realize not only the extraordinary coherence of events but also the immense progress achieved, for the cell could henceforth satisfy its energy requirements with a minimum consumption of substances.

Moreover, the layer of ozone, which one might have thought detrimental, was to make it possible for organisms to extend their territory and invade the earth, after emerging from the water. As life originated some 3,500 million years ago, the chemical changes that we have described are likely to have been spread over a period of about 1,000 million years. But this temporal difficulty, if it exists (for we have no idea, of course, of the kinetics of the processes in question), has certainly now been solved, as the original molecules of prebiotic evolution belong to interstellar space which, in conjunction with the original nebula, goes back 6,000 million years, and as, furthermore, substances are found in carbonaceous meteorites and comets which approach even more closely the final molecular state.

Reductibility of life to the laws of physics

On pages 31-3, we put forward the view that matter, whether inanimate or animate, was governed by a single and universal law, expressed by the two aspects in question. The recent history of science provides us with a specific and palpable analogy which substantiates this general notion [1, 2, 68–75]. It was Lavoisier who, towards the end of the eighteenth century, introduced the spirit of physics into chemistry by applying the principle of the conservation of mass to chemical reactions. This was a great step forward; but as soon as the idea of molecular structure took shape, as a result of the research of Le Bel, Van't Hoff and Kékulé, that of chemical bonding, which is really the heart and soul, as it were, of molecular architecture, needed to be further investigated.

Classical physics tried, in vain, by resorting to every imaginable expedient, to solve this crucial problem on which the future of chemistry depended. But it was not until 1927, in the light of quantum mechanics, which had just made its appearance, that Heitler and London were able to find the answer to this problem that had baffled Newtonian mechanics. It is a most remarkable fact that it was some of the great founders of modern physics, namely Niels Bohr, Erwin Schrödinger, Werner Heisenberg and Eugene Wigner, who asked themselves the corresponding question with re-

Extraterrestrial life

In other planetary systems with a longer life expectancy than that of the solar planets, one might have expected that in the course of time, pluricellular organisms would have developed far beyond those we know [64–66]. But such a vision of things calls for serious reservations, in view of the observations made on pages 31-3 on the role of the molecular weight of DNA in the transformation process.

In 1944, Kant's brilliant theory concerning the origin of the solar system was given a new impetus by von Weizsäcker and Kuiper. Their findings together with subsequent research have led to the conviction that the system is a particular result of the general process of formation of the stars. This means that our galaxy is very well supplied with planets and, according to Shapley, contains as many as about 100,000 million of them in which the prevailing conditions are similar to those on earth, particularly as regards temperature, dimensions and, inevitably, the molecular environment. There are perhaps 10^{20} of them in all the galaxies visible through a powerful telescope. It may thus be concluded that the prebiotic phenomenon itself is universal, but that its degree of progress clearly depends on the conditions peculiar to each system.

Furthermore, one is justified in questioning whether life outside this earth might not be based on some substance other than carbon. Among all the substances that have been thought of, silicon is the one to which the most attention has been paid, doubtless because it is closely related to carbon in the same column of the periodic table and because, consequently, its properties are, by definition, similar. Life, however, is based not on general properties but far more on slight differences, and even the apparently slight differences between these two types of atom are precisely the ones that are important.

Now, many types of carbonaceous molecule, including nucleic bases, possess exceptionally versatile properties. These are doubtless unique, by virtue of their π electrons,[1] connected with an inherent delocalization on account of the need to be relatively stable in order to subsist and, at the same time, sufficiently unstable in order to evolve. It is on this species of contradiction that life is based for, precisely, nucleic acids are built up on constituents of an aromatic nature.

These basic properties have no counterpart among silico-organic derivatives [67], of which there is moreover barely any trace in the universe—other than on earth—where silicon is 150 times more abundant than carbon. Hence it is highly probable that life everywhere is based on carbon, which is thus a unique element within the periodic system of the elements.

1. π or valence electrons serve as chemical bonds inside the molecule.

gard to biology. The developments in wave mechanics, which was initiated by Louis de Broglie, have shown that the electron is subject to a principle of complementarity which makes it impossible to know simultaneously and precisely what its position and speed are. In an ideally conducted experiment, on a microscopic scale, this situation is the result of the indeterminism governing the effects produced by the means employed to measure them.

Similarly, it might be emphasized that the means used in order to broaden our knowledge of organisms are liable to bring about changes in them of such a kind that we shall never be able to penetrate their ultimate secrets. If this proved to be so, to pursue the analogy, we should have to convince ourselves that, as with the action quantum h, which is irreducible in atomic physics, the notion of life is also an initial assumption of biology. It is perhaps excessive to go as far as this, by extrapolating from one scale to another, and, accordingly, such a conclusion can be accepted only as an imaginative possibility. It seems much more reasonable to conclude, as Heisenberg does, that a grasp of the concept of life presupposes, as with chemistry itself, the formulation of a conceptual whole within which inanimate matter is an extreme case in which the phenomenon of life consequently plays no more than an extremely minor role, like that of non-gravitational forces in the movement of the planets.

We may thus conjecture that if physics, with its methods and laws, today extols to a quite extraordinary extent the developments in biology, it is the latter which, in future, will impose a broader outlook on the so-called basic sciences. In the same way, ever more startling observations of the cosmos have repercussions on physics, stimulating it to surpass itself by confronting it with a state of matter which, because of its unfamiliarity, inevitably entails a revision of the principles of physics.

The evolution of the cosmos

In addition to chemical evolution which we have just described, there is the evolution of the universe, which is related to nuclear events [76, 77]. Our galaxy, formed some 10,000 million years ago and having a diameter of about 10^5 light-years, has a total mass equal to about 200,000 million times that of the sun (the latter being a marginal star gravitating some 30,000 light-years from the galactic centre). The universe is full of similar galaxies, each of them containing thousands of millions of stars, whose autonomy is a function of the distance separating them which reaches some ten times the diameter of the largest galaxy. On the other hand, these colossal objects sometimes group themselves together and then form what are called large clusters.

It is generally recognized now that the first stars were formed inside a nebula, so that interstellar gas and dust are the materials of which they are composed. The first stage is the formation of what is called a proto-star, a process lasting at least 100,000 years and, in most cases, several million years. Subsequently, the stars, which are the seat of thermonuclear reactions, derive their energy from the fusion of four nuclei of hydrogen into one nucleus of helium, which necessitates internal temperatures of some 10 million degrees: such is the case with the sun. But a second stage occurs in which the helium is itself transformed into carbon and oxygen, necessitating temperatures of hundreds of millions of degrees, while for the formation of heavier elements such as magnesium, silicon, iron, copper and nickel, temperatures ten times higher still are needed.

Some stars consume their nuclear fuel at such a prodigious rate that they have a life of only a few million years, whereas most of them are singularly calm, like the sun, and have already existed for several thousand million years and will survive as long again. A star's evolution leads inevitably towards its extinction when it becomes a white dwarf, a neutron star, or possibly a black hole. However, stars with a greater mass than a critical mass, Mc (in the region of 1.44 to 2.5 times the solar mass), are obliged to eject matter, fragment or explode, before their residuum (with a mass less than Mc) can reach the first two above-mentioned stages. It is likely that the phenomenon known by the name of supernova, a kind of evolutionary accident which flings into space the heavy elements built up in a large portion of the star, is one of the most effective means whereby this reduction of mass occurs.

The extent of our ignorance

We can gauge the extent of our ignorance simply by tackling the subject of antimatter or that of quasars, which are extragalactic objects of one light-year or so in size; or, again, that of pulsars which belong to our own galaxy and measure only some 100 km —these are neutron stars having densities reaching incredible values, in the region of 10^{15} g/cm^3. Once again, one can see how much truth there is in the claim that we are still very far from having reached a fully synoptic view of the significance of the concept of matter.

Nor is it only the stars that are in process of evolving: since 1922, on the basis of general theory of relativity which had led Einstein to propound a static universe, we have known, thanks to the work of A. Friedman and a little later G. Lemaître, that theories postulating an expanding universe exist and that they correspond most closely with present observations, as research has consistently confirmed ever since Hubble's discovery, in 1928, of the 'red shift' of extragalactic nebulae. But what will be the outcome of this expansion? The following two possibilities may at any rate be envisaged.

Either the expansion currently observed, and which must have started some 15,000 million years ago, in a state of extreme compaction, will go on indefinitely and the density will tend towards zero, that is to say towards the void; or else the spreading process which has brought the universe to its present state will continue for 30,000 million more years or so and, through a symmetrical phase of contraction (oscillating solutions also exist), it will take 45,000 million years to return to its initial state before beginning the same process all over again.

Thus, everything in nature evolves at all levels—nuclear, atomic, molecular and cosmic. Why therefore should life, wherever it occurs in the universe, escape this process, of which it clearly forms such a stupendous branch, as it contains all scales within itself?

General conclusions

Whereas, 500 years ago, the scientific discoveries of Copernicus were the immediate cause of the split between philosophy and physics, in the case of biology, on the other hand, such a situation only came about much later. For a long time biology remained under the influence of scholasticism, despite the efforts of great researchers such as Harvey, Spallanzani, Laplace and Lavoisier—in fact, up to about the middle of the nineteenth century. It was finally because of Claude Bernard, in particular, that the separation took place [78] thereby, through the elimination of traditional concepts such as the soul, vital force and final cause (which had up to then been used to explain everything), making it possible to establish the foundations of physiology. Paradoxically, it is thus our scientific knowledge which, while giving a progressive stimulus to the world and enabling it to develop in an unprecedented way through prodigious applications of that knowledge, has at the same time given rise to apparently harmful consequences.

Those who played a part in founding vitalism and animism [79, 80] were at the same time both right and wrong. They were right in that these concepts, though extremely vague, reflected a deep intuition whose meaning we are only now able to transcend by broadening it and seeing it in terms of universal processes, thus bringing about an alliance between nature and life. They were wrong in that these concepts were to a certain extent the very negation of scientific progress which was so indispensable to the well-being of humanity. The universe is our cradle. The area of near-certainty as regards the prebiotic stage, will inevitably be extended to include living beings themselves as and when discoveries are made in the future provided that research continues in every direction, at the level of observation, experiment and theory. If a closed and cyclical universe [81, 82] were one day to compel our recognition, we should return to a situation which Heraclitus was the first to visualize, and which was later developed by Zeno of Citium, the founder of Stoicism, in the third century B.C. [83, 84].

As to the nucleic acids, it is now understood that the programming faculty attributed to them must be assigned to interstellar space, as they are inevitably the result of a strict determinism the prime cause of which must necessarily be interstellar space. As regards the proteins, they organize themselves without difficulty, at any rate in the form of proteinoids and, in any case, their constituents are profusely distributed throughout the universe. Moreover, this means that it is not necessary for the nucleic acids to have pre-existed them. Such are some of the stupendous findings of modern science which explain an immense phenomenon in time and space for, as a result of prebiotic evolution, all the essential constituents are everywhere at the disposal of a second and magnificent phase—namely the biotic phase itself.

The significance of feedback

There must, however, be no misunderstanding, for the differentiation between individuals of the same species clearly demonstrates that evolution depends partly on feedback effects. This means, in other words, that the programming to which we have referred is far from being absolute, as the medium—in which the nucleic acids which are the bearers of information develop—also conditions and selects the developments [85, 86]. When I refer to the medium, I am thinking primarily not only of cytoplasm but also of histones, whose role in its interactions with DNA (as yet barely glimpsed) must be quite considerable. In my opinion, this protein, through a mechanism that remains obscure, determines the individual's personality and is even capable in the course of existence, under the impact of the biochemical environment, of causing some genes to disappear by masking them, and unmasking others which had remained latent, thereby causing them to appear. This would seem to be an extremely subtle process with implications for the individual in his entirety.

We are still far from transcending matter, in its full generality. The fact that new concepts seem likely to be formulated at the level of elementary particles which will turn us aside from quantum mechanics, which is valid for the intermediate domain and applicable to molecules and molecular groupings, is in itself a sufficient indication that at the level of living beings more universal concepts, of which we as yet know nothing, will be found to be indispensable.

Then we shall no doubt grasp the underlying unity of matter, with its truly miraculous subtlety governing its different states, and we shall no doubt be better able to appreciate that life is the expression of the most universal laws and that death is the renunciation of them and involves the reduction of living matter to inanimate matter which is subject to laws of more limited scope.

We are thus brought back to the Old Testament vision, but in an infinitely more majestic form and more firmly based on the solid hopes afforded by greater scientific knowledge which can henceforth serve as a basis for the development of a new philosophy ensuring man's definitive reintegration in the universe. □

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The quark's model and confinement

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The idea of elementary or fundamental particles has always been a very fruitful one in the study of the structure of matter. The very notion of elementarity is determined by the boundaries of our knowledge, and thus progress in our understanding of the structure of matter can be represented as a transition from one level of elementarity to another. In the case of the recently postulated 'quarks', there is even no need to assume that they exist; they enter into theory purely as a mathematical concept. But if quarks really exist, their model will have a number of unexpected features.

As recently as ten to fifteen years ago, particles such as the proton and neutron were assumed to be elementary—along with many others. There was not sufficiently strong experimental and theoretical evidence to postulate the existence of 'more elementary' particles which could be considered as components of the proton, the neutron, and so on.

Nowadays our theoretical ideas are based on the fact that these more elementary particles do, in fact, exist. They are called 'quarks'. Many experiments are being directed towards verifying the details of the quark hypothesis of the structure of matter. It might be said that physics is moving in the direction of a new, quark, level of elementarity.

The quark model involves, however, a number of unanticipated features. It requires the introduction of new types of properties and it assumes that quarks must be 'confined', that is, that they cannot be observed in the free state.

Internal symmetry, SU(3)

The concept of internal symmetry is basic to the ordering of our ideas on elementary particles. This symmetry describes the most general properties of particle interactions and enables us to draw conclusions about quantities which are conserved without our having any detailed knowledge of the interparticle forces. From the opposite point of view, the existence of a conservation law indicates the presence of a certain symmetry. Let us consider the reaction $A + B \rightarrow C + D$, initiated by the collision of particles A and B. The conservation of a quantity, Q, means that its value in the system of initial particles $Q(A + B)$ is equal to that in the final state, $Q(C + D)$: $Q(A + B) = Q(C + D)$. This becomes particularly clear when Q is additive, i.e. $Q(A + B) = Q(A) + Q(B)$. The conservation of Q can then be expressed very simply as $Q(A) + Q(B) = Q(C) + Q(D)$. If the additive quantity, $Q(A)$, is independent of the state of motion

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of particle A, then Q describes an internal symmetry. Such quantities are sometimes called charges because electrical charge belongs to this class of quantities.

Elementary particles take part in three main types of interaction: strong, electromagnetic and weak.[1] Their forces are in the ratio $1 : 10^{-2} : 10^{-5}$. Here we are interested only in strong interaction and its related symmetries. The strongly interacting particles are known as hadrons.

The hadrons can be divided into two

1. Missing from our list of interactions is, of course, the fourth: gravity.

The excitement and practicality of physics

Physics now is not just a development of the physics of twenty years ago. It is quite new. It turns corners. There are always surprises. Not the sort of surprises you find in investigating a mechanism, as in physiology, but surprises that evoke ideas that did not exist before. I don't think that physics will ever have an end. I think that the novelty of nature is such that its variety will be infinite—not just in changing forms but in the profundity of insight and the newness of ideas that will be necessary to find some sort of clarity and order in it. I think that the only thing you can compare it to is the mystical idea of God with infinite attributes.

Physics is that sort of thing in a tangible form. In addition, you acquire modes of thought that apply to other things—not only to physics. It opens doors to new forms of thought. It has not had any real application in our society, because the people who might use it, in politics and so on, just have no idea about it. They have not been educated in what exists and what is at hand. It's a great pity that the general public has very little inkling of the tremendous excitement—intellectual and emotional excitement—that goes on in the advanced fields of physics.

I think [the gap can be bridged] only by drastic action, and I think this is necessary to preserve the human race. It may come—but not in my lifetime. I think that physics should be the central study in all schools. I don't mean physics as it is usually taught—very badly, as a bunch of tricks—but, rather, an appreciation of what it means, and a feeling for it. I don't want to turn everybody into a scientist, but everybody has to be enough of a scientist to see the world as something that is tremendously important beyond himself, to be able to appreciate the human spirit that could discover these things, that could make... instruments to inquire and advance into its own nature. I rate this so highly that I have a feeling that with this education people would find something above their everyday lives, above their nationality, even above their religious affiliations, and find a basic unity in the spirit of man.

Isidor I. Rabi, as quoted by Jeremy Bernstein, *Profiles: Physicist—I.*

main classes: baryons and mesons. Baryons have integral baryon charge B; for mesons the value of B is equal to zero. Baryons are fermions, i.e. their angular momentum is equal to half odd-integral multiples of Planck's constant **h**; mesons are bosons, i.e. their angular momentum is equal to integral multiples of **h**.[1] The further classification of baryons and mesons depends on the internal symmetry. The special feature of this symmetry is that hadrons exist in families —multiplets—in which all the members have approximately the same mass. This approximate equality in mass is a result of the fact that the internal symmetry is itself approximate, as symmetry of only the strong interactions, and is not valid for electromagnetic and weak interactions. The individual particles in a multiplet can be identified by their additive charges. The number of particles in the multiplets and the set of additive particle charges fully define the type of symmetry.

The strong hadron interaction possesses SU(3) symmetry (according to Gell-Mann and Ne'eman), in which the particles are distinguished by two additive charges: isospin projection, I_3, and strangeness, S. These quantities, together with the baryon charge, form the electrical charge of the particle: $Q = I_3 + 1/2(B + S)$. The value of I_3 takes only half-integral or integral values and the strangeness, S, can only be integral. As a result, the electric charge must be integral (in units of the electron charge) —a fact which is in full agreement with experiment. According to SU(3) symmetry, mesons may occur in multiplets consisting of 1 particle, 8 particles, 27 particles, and so on; for baryons the possible multiplets with the lowest numbers of particles have 1, 8 and 10 members. To give some examples, the baryon octet consists of the particles $N^{+,\circ}$, $\Sigma^{\pm,\circ}$, $\Xi^{-,\circ}$, Λ, the baryon decuplet includes particles $\Sigma^\star$, Ω, Δ, $N^\star$, and the meson octet of the particles $K^{\pm}$,K°, K°_2, $\pi^{\pm,\circ}$, η. The values of the charges of some particles are shown in Table 1.

TABLE 1. Values of various charges

	I_3	S	Q
$\pi\pm$	± 1	0	± 1
K^+	1/2	1	1
pN^+	1/2	0	1
Δ^{++}	3/2	0	2
Ω	0	-3	-1

SU(3) symmetry has brought a certain orderliness into the over-all picture of the hadron world; all known baryons can be placed in singlets, octets and decuplets. SU(3) also predicts, however, the existence of other multiplets (with smaller and greater numbers of particles) which are not found in nature.

TABLE 2. Minimal quark combinations

	I_3	S	Q
Quarks			
u	1/2	0	2/3
d	$-1/2$	0	$-1/3$
s	0	-1	$-1/3$
Antiquarks			
$\bar{u}$	$-1/2$	0	$-2/3$
$\bar{d}$	1/2	0	1/3
$\bar{s}$	0	1	1/3

Quark model

SU(3) has not only explained some features of the hadron spectrum but has also greatly stimulated ideas about hadron structure. Mathematically, within SU(3) there is also a multiplet of three particles (triplet). This is the simplest multiplet, not only because

1. The elementary quantum of action, Planck's constant (**h**), is a universal constant which, if multiplied by the frequency of a quantum of energy, yields the *quantum energy*. Value: $6.6256 \cdot 10^{27}$ erg sec, or $6.6256 \cdot 10^{-34}$ Joule sec. The value $\mathbf{h}/2\pi$ is written **h**.

it contains the smallest non-trivial number of particles but also because it enables us to understand from a mathematical point of view the charges of all the other multiplets. In the same way that we can construct tensors of any rank from vectors and states with any value of spin from spinors of spin 1/2 so in SU(3) we can construct the state of any multiplet from the functions which describe a triplet. The triplet states are called quarks (Gell-Mann and Zweig). Of course, there also exist states corresponding to 'antiquarks'. All the additive charges of antiquarks are opposite in sign to those of quarks. In contrast to the experimentally observed hadrons, quarks have fractional electric and baryon charges (see Table 2).

The idea of quarks can be used to provide a simple and elegant description of the charges of all known hadrons. For this purpose, there is no need to assume that quarks really exist—they only come into the theory as a mathematical concept. The minimal quark combinations required to describe hadrons can easily be found from Table 2 and the additive property of charges. Thus, for example, in order to get a baryon number of zero, we have to combine a quark and an antiquark. This means that meson charges are the same as those in a quark-antiquark system. The charges of the π^+ meson are identical to those of a $u\bar{d}$ system; the charges of the K^+ meson are identical to those of the $u\bar{s}$ system, and the π^- meson can be compared to $\bar{u}d$.

For baryons, the baryon charge is equal to 1; therefore the minimal combination giving this charge must consist of three quarks—baryons have the same charges as a system of three quarks. Thus, for example, the charges of the Δ^{++} particle are equal to those of the uuu system and the Ω^- particle is characterized by the same charges as the quark system sss.

In this quark language we can easily understand just which multiplets of the SU(3) symmetry are missing in nature: it is those which cannot be related to minimal quark combinations. For mesons this means quark combinations with several quark-antiquark pairs of the type $u\bar{d}s\bar{s}$, $u\bar{d}s\bar{s}u\bar{u}$; for baryons it means three quarks plus a certain number of quark-antiquark pairs such as $uuud\bar{d}$ or $uuud\bar{d}s\bar{s}$.

Are quarks real?

The possibility of reducing certain properties of multiplet hadrons to those of quarks, considered as mathematical objects in SU(3) symmetry, naturally raises the question as to whether this does not imply that quarks are real particles making up the component parts of hadrons. The main objection to treating quarks as real particles is that they would necessarily have fractional electric and baryon charges. Such particles have never been observed and this is a serious difficulty. The quark model was first accepted purely as a working hypothesis. Its unexpected success in explaining a wide range of phenomena showed that it can be used as a basis for the theoretical correlation of experimental data. Moreover, recent theoretical work has indicated that the quark model can also in all probability be used to develop a phenomenological theory of hadrons.

It is assumed in the quark model that hadrons are bound states of fundamental particles (quarks). Mesons consist of a quark and an antiquark and baryons of three quarks. The idea of quarks as real particles introduces important consequences. The first of these is that such a quark must obey the statistics of real particles. The second is that as a quark can move inside a hadron, the different states of motion of such quarks will manifest themselves as hadrons of different masses.

We first consider the problem of statistics. If all hadrons, bosons and fermions can be made out of quarks, then quarks must be fermions. Half-integral spins can be used to produce integral spin, but the opposite is not true. If the quark is a fermion it must be subject to the Pauli exclusion principle. This means that two identical quarks cannot be in the same state of motion.[1] The question then arises of how to obtain a baryon from three identical quarks. How can we, for example, construct a Δ^{++} particle which must contain three identical quarks, uuu? On the one hand, the energy would be a minimum if the quarks were in identical states; on the other hand, this is forbidden by the exclusion principle.

This difficulty can be overcome if we admit the possibility of three types of quark (in the Δ^{++} particle, for example) with the same charges. This means that in addition to baryon charge, electric charge, strangeness and the other properties mentioned above, we must now endow the quark with a new property which would distinguish the three types in the Δ^{++} and other hadrons.

Two new ingredients: colour and charm

This additional property, which in principle must be determined experimentally, has received the conventional but graphic name of 'colour'. It is thus assumed that every quark exists in three colours—red, blue and white—so that instead of three quarks we must now consider nine. However, it has not proved possible to distinguish different colours of quarks experimentally. We might say that, if coloured quarks do exist, then physics is colour-blind.

The last three years have been remarkable for the discovery of heavy, but highly stable, particles which have been called psions. The lightest of these was first found in 1974 at Brookhaven and Stanford and has a mass three times that of the proton. The stability of these psions can only be explained by assuming that there exists another conservation law in nature which holds exactly in strong and electromagnetic interactions: in the absence of weak interactions, the psions would be absolutely stable. The new quantity which is conserved in strong and electromagnetic interactions must belong to an internal symmetry in the same way as strangeness and isospin projection. This quantity has become known as 'charm'. In the quark model, the appearance of charm means that in addition to normal 'uncharmed' quarks we must also have another quark which can carry the new property. The number of quarks is thus again increased. We now have four quarks, each of which exists in three colours (see Table 3).

TABLE 3. The four quarks, their three colours, and charm

	B	S	Q	Charm
u	1/3	0	2/3	0
d	1/3	0	−1/3	0
s	1/3	1	−1/3	0
c	1/3	0	2/3	1

An important role in the acceptance of the quark model has been played by experiments on proton-proton scattering and on the production of hadrons by electron and positron collisions and neutron scattering by protons. These experiments have confirmed the 'grain' structure of the proton and have shown that the proton interacts not as a unit but as an assembly of subparticles. These subparticles have a point structure and the interaction takes place with each of them separately. In particular, electromagnetic interactions occur over a region of space of the order of 10^{-15} cm, whereas the size of the proton is measured in units of 10^{-13} cm. Calculations of the electric charges of the subparticles have shown that they are just those fractional values (2/3, 1/3, 1/3) which are characteristic of quarks. The spin values are also right for quarks.

1. More explicitly, the Pauli exclusion principle affirms that, in any system, no two identical fermions (particles of spin 1/2) can occupy states having the same set of quantum numbers. The principle applies to neutrons and protons. It does not hold for bosons, π-mesons and photons.

Quark interaction and 'confinement'

A system of a quark and an antiquark ($u\bar{d}$, for example) cannot describe one particular meson, as suggested by SU(3) symmetry. The two particles move relative to one another, and there exists an infinite set of quantum states for this motion. For a quark, u, and antiquark, $\bar{d}$, all these states have the same charges. Only the state with the smallest energy can be identified with the π^+ meson; the remaining states can be called states of the excited π^+ meson. These states correspond to particles of the π^+ type but with a greater mass. The spin might also be different from that of the π^+ since a system of quark and antiquark can have various angular momenta. Thus a single state constructed from mathematical quarks becomes in the quark model an infinite set of states—particles which differ in mass and angular momentum. Meson families of this type are, in fact, observed: the relation between the particle mass, M, and the angular momentum (spin) J is very simple: $M^2 = AJ + B$, where A and B are constants.

Similarly, a system of three connected quarks gives a spectrum of baryon states with different masses and angular momenta. The particle with the smallest mass corresponds to a stable baryon (proton, neutron, etc.) and the higher states describe excited baryons. The whole family of particles obtained from a particular three-quark system has identical charges. Experiment shows that the relation between baryon mass and angular momentum has the same form as for mesons: $M^2 = AJ + B'$. This means that the quark-antiquark and quark-quark interactions are almost identical inside the hadron.

In quantum mechanics the eigenvalues[1] of angular momentum J can only take certain definite values (in units of Planck's constant $\mathbf{h}$) which are integral for mesons, $J = 0, 1, 2, \ldots$, and half-integral for baryons, $J = 1/2, 3/2, \ldots$. Thus the equation $M^2 = AJ + B'$ describes a spectrum where the squares of the masses of consecutive particles differ by an amount A. This spectrum is reminiscent of that for a simple continuous string. When a string vibrates, the energy levels of the harmonics follow the natural integers and form a ladder of equally spaced steps. We can say that the effective interaction of quarks in a hadron has a string-like character when we consider the spectrum of states. This analogy is often used to depict mesons as a quark and antiquark joined by a string and baryons as three quarks again joined by strings.

The success of the quark model in explaining many aspects of hadron physics has naturally presented experimenters with the problem of finding quarks in the free state and, thus, of demonstrating that they really exist. The search for quarks has been pursued during the last decade in many laboratories throughout the world but it has always been unsuccessful, although in principle it should not be difficult to find a particle with a fractional charge. The failure of the accelerator experiments might be explained if the quark mass, M, were too large for quarks to be produced even in the biggest machines. This would imply that M is greater than ten proton masses. A particle with this kind of mass could be found in cosmic rays but, here again, the results have been negative. Thus theory must now explain the absence of free quarks. Although the traditional explanation (very large masses) is not yet excluded, most physicists believe that the absence of free quarks is fundamental: quarks can only exist in a bound state.

When property becomes principle

The problem of quark 'confinement' is a new one in elementary-particle physics. Up till now, fundamental restrictions on the

1. The eigenvalue, in calculus, is a special value of a (given) parameter of a differential equation for which a non-trivial solution—or an eigenfunction—exists.

possibility of detecting particles in the free state have never been considered. This property of quarks is now being elevated to the level of a principle and studies are being made of the possible mechanisms responsible for this confinement.

The mechanism must at least account for the following properties of quarks in hadrons: (a) in the case of small interquark distances, the quarks must behave as individualized particles and the hadron must have a grain structure; (b) at large distances, the quarks must hold together so that they are not observed outside the hadron; (c) hadrons must be colourless; (d) the spectrum of hadron states (M^2) must be linear in respect of J.

Theories dealing with quark confinement can be divided into two classes: those where the aim is to find a mechanism to produce the confinement and those in which this confinement is used as the starting-point of the theory.

Although the search for a confinement mechanism has not yet produced final results, the idea of coloured monopoles is very promising. We can explain this idea with the example of a magnet. It is well known that the magnetic properties of matter can be described by means of magnetic charges, or monopoles, as the fundamental elements. Yet such charges do not exist in nature, and if we break a bar magnet in half we get two bar magnets and not opposite magnetic charges. If we now return to the quark model, a monopole corresponds to a quark and magnetic charge to the colour of the quark. But the property described by colour is more complex than magnetic charge. In particular, a neutral colour must be obtained not only by the addition of opposite colours (quark-antiquark) but also by the combination of three different colours (blue, red and white in a baryon).

In the hypothetical case of two dimensions (time and one spatial co-ordinate), it can be shown that this idea produces a potential between the quarks which increases with distance and which holds the quarks in confinement. It has not been possible to carry out similar calculations in real four-dimensional space.

Finally, quarks, gluons and 'bag models'

The idea of a potential or forces between quarks is a secondary one in elementary-particle theory. The main concept is the interaction between quarks and other particles which are called gluons (in order to stress their binding function). The quark interaction consists of an interchange of gluons. The type of gluon involved determines the form of the interquark potential.

The conditions which must be satisfied by the quark model impose quite strict limits on the possible types of gluon. They must be particles with spin 1 and possess a coloured charge. Since gluons have colour they cannot be observed in isolation and can only exist inside hadrons. The theory of quark interaction and coloured gluons is quite complicated and the calculation of bound quark states on the basis of this theory will probably take some considerable time.

The difficulties of quark and gluon theory highlight the necessity of developing a phenomenological theory of hadrons which would in particular contain the idea of quark and gluon confinement. This implies a relativistic description of an extended complex particle made up of gluons and quarks and inside which the density of hadron matter is high. Such a description would have to satisfy the same conditions as the quark model. It would also have to be simple, to include the smallest number of parameters and to satisfy the experimental data.

The first step in this direction has been taken in the 'bag models'. Since quarks are strongly bound they can change their properties. Thus if quarks and gluons are assumed to be confined to some type of bag —a region of space bounded by surface tension—we might expect new results to appear. The quarks and gluons can move freely inside the bags but they cannot get out. One type of bag is called the MIT bag, while another (the SLAC bag) actually consists of two bags (an outer one and an inner one), and the quarks and gluons move in the space between them. A collision between two hadrons in these models is a collision between two bags and can lead to a redistribution of the quarks between the new bags, though no single quark can become isolated and neither bag can acquire colour.

Briefly recounted, then, this is where particle physicists stand in their research on quarks and related phenomena. Only future experiments with high-energy hadrons can determine what is an adequate model for hadrons. □

To delve more deeply

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Energetic nuclei, superdensity and biomedicine

A. M. Baldin

Physics of high-energy nuclei: astrophysical aspects

Like many other particles in high-energy physics, relativistic nuclei were first observed in cosmic rays. These nuclei convey very valuable information about the source of cosmic rays and its chemical composition and about the intergalactic environment through which the nuclei have come. This information nevertheless still has to be deciphered. It is clear that as the nuclei travel through space they 'split', and that part of the spectrum corresponding to light nuclei becomes enriched while the part corresponding to heavy nuclei becomes impoverished. This calls for a careful study to be made of the mechanism by which the nuclei split (known as fragmentation), and for the value of the relevant cross-sections to be determined.

As evaluation show, a 10 per cent error in the fragmentations cross-section and in the flux values for nuclei of the various groups leads to 100 per cent errors in the values for the quantity of matter through which the cosmic rays have passed. For the flux ratios for nuclei with various atomic numbers to remain relatively constant as the nuclei journey from their source till they enter the earth's atmosphere, the quantity of matter encountered on their way must not be significantly higher than 4 g/cm^2. This corresponds to their having an average age of 10^8 years if the average density of intergalactic hydrogen is 0.01 atoms per cm^3.

The relative fluxes (abundances) of nuclei in cosmic rays are shown in Figure 1; these data were gathered by satellite.[1] The continuous line shows the abundances of nuclei in cosmic rays and the broken line those of elements in the solar system. The particularly sharp difference in the abundances of lithium, beryllium and boron nuclei could perhaps be explained by the mechanism of heavy nucleus fragmentation in the cosmic rays. On the other hand, how is the preponderance of heavy nuclei in cosmic rays to be explained? It is hard to imagine any cosmic accelaration mechanism which would give such a clear advantage to heavy nuclei.

All acceleration mechanisms depend on the ratio of particle charge to particle mass, and this ratio changes slightly over the range of Mendeleev's periodic table. It is possible that the observable abundances of nuclei in cosmic rays afford evidence that the composition of the elements in the area where cosmic rays originate differs markedly from that of the elements in the solar system. It is not impossible that these areas consist entirely of nuclear matter.

Accelerator studies on the collisions of relativistic nuclei should shed considerable light on these important problems both as regards (a) understanding the mechanisms governing the collision of relativistic nuclei and their passage through matter and (b) the calibration of apparatus for studying the composition of cosmic rays.

One important aspect is elucidation of the possibility of a theoretical description of superdense stars and other astronomical objects composed of nuclear matter. The collision of nuclei moving at the speed of light, and hence at speeds greater than

1. cf. P. Meyer, R. Ramaty and W. Weber, in: *Proc. Topical Meeting Trieste*, 1974, p. 234.

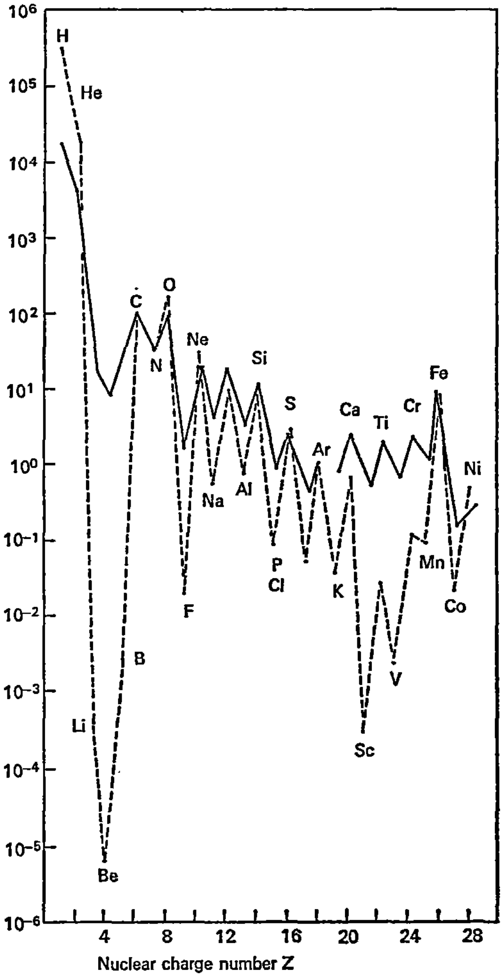

FIG. 1. The graphs depict the relative fluxes (or abundances) of nuclei in cosmic rays, as shown by the continuous line, and the abundances of elements in our solar system (broken line).

that of sound, in nuclear matter should be accompanied by collective movements of nuclear matter of the shock-wave type. When this occurs, the resulting density of the nuclear matter should be greater than the density of the matter of the proton. With a certain degree of approximation, it is possible to describe these phenomena with the aid of hydrodynamics which will make it possible to establish the equation of the state of nuclear matter in such extreme conditions. Knowledge of the equation of the state of nuclear matter is of very great importance in attempts to describe astronomical objects, the evolution of stars and gravitational collapse. Producing beams of relativistic nuclei in laboratory conditions, accordingly, not only provides an opportunity for analysing the composition of cosmic rays but also for carrying out experimental verification of hypotheses about the principles governing the behaviour of nuclear matter at high and super-high temperatures.

Nuclear physics

Very interesting hypotheses have recently been put forward about the possible existence in nature of density isomers in nuclear matter. Just as with the aid of high pressures it is possible to modify ordinary substances and obtain diamonds or metallic hydrogen, it may be possible, using the collisions of high-energy nuclei, to obtain a new (although for the time being hypothetical!) composition of nuclear matter possessing unusual properties. It is possible that this new substance may last for a relatively long time and be metastable.

An important feature of the collisions of high-energy nuclei is that enormous energies are concentrated not at a point but in areas of space which are considerable in comparison with the size of elementary particles. It is extremely important to make sure that when such a collision occurs, dissipation of energy takes place and many degrees of freedom are generated, so that the representation of a continuous medium may be correct and it may be possible to speak of pressure and temperature.

One such experiment involves the collision of a relativistic nucleus of oxygen with a nucleus of bromine or silver in a nuclear emulsion. The oxygen nuclei were accelerated in the Dubna proton-synchroton up to energies of 60 GeV, then extracted from the accelerator and focused and directed on the recording apparatus. A group of physicists led by K. D. Tolstov discovered that the complete disintegration of the colliding nuclei into their component nucleons occurs not only through the action of relativistic oxygen nuclei but also, with a probability of several per cent, under the influence of protons, and the number of particles emitted runs into hundreds. This shows that in a considerable number of cases, dissipation of energy takes place and many degrees of freedom are generated and that a large number not only of nucleons but also of pi-mesons appears. It may be expected that since the colliding nucleus (having, let us say, a diameter less than the target nucleus) moves within the target nucleus at supersonic speed and carries the substance of the target nucleus away, a shock-wave front may be formed.

Hypotheses of this kind were put forward in the literature as long ago as the 1950s, and observations of a maximum at an angle of 60° (to the direction of the collision) in the angular distribution of the reaction products from the fragmentation of nuclei are now being interpreted in this way by some physicists. These observations were made by Polish physicists in 1965 on the basis of the irradiation of a xenon bubble chamber with beams of pi-mesons from the Dubna proton-synchrotron (P. Zelinsky *et al.*).

An intensive investigation of this phenomenon was recently conducted by physicists from the Federal Republic of Germany (V. Grainer, E. Schopper *et al.*) using the accelerators at Berkeley (California) and Dubna.

The German physicists are hoping through study of this maximum (being interpreted as a Mach cone) to discover a superdense state of nuclear matter, an isomer of density. At the high energies corresponding to the critical pressure (if density isomers exist), the Mach cone should disappear. According to these physicists, in the energy region so far achieved only in the Dubna proton-synchrotron, a negative pressure should appear, annihilating the Mach cone. Quite apart from verification of the hypothesis about the existence of density isomers, obtaining extreme states in nuclear material is of enormous scientific interest. There is also no doubt that when high-energy multicharge ions collide with nuclei, we are in the presence of new kinds of collective movement of nuclear matter.

Biomedical research

The use of accelerated nuclei is also of great practical importance. Almost no study has been made of the passage through matter of relativistic multicharge particles. Without any detailed research into the processes of the atomic collision of relativistic nuclei, it is difficult to rely on the precision measurement of nuclear interactions. Study of the passage of multicharge particles through a substance is of great interest not only from the point of view of verifying existing hypotheses about the nature of cosmic rays but also from the point of view of protecting astronauts and space apparatus from radiation. In certain circumstances, relativistic nuclei represent the greatest radiation hazard in space.

In order to evaluate the hazard from heavy particles accurately and to predict the development of radiation injuries, the peculiarities of the action of these particles on various biological systems must be studied from all angles. The use of spacecraft, satellites and stratospheric balloons for these purposes is very expensive and is dependent on considerable technical difficulties being surmounted; in addition, cosmic radiation is of low intensity and great expenditure of time is called for. Now that it is possible to obtain beams of relativistic nuclei in laboratory conditions there is a solid basis for this research.

Particularly valuable information can be obtained with the help of the propane chamber of the High-Energy Laboratory of the Dubna Joint Institute for Nuclear Research (JINR), in which it is possible to observe all the processes associated with the passage of heavy particles through hydrocarbons. One of the chief motives for obtaining beams of relativistic nuclei in the United States was, in fact, the opportunity this offered for research into a number of medical and biological problems.

To delve more deeply

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Explorations in mathematics

Charles Musès

Between what we call the subjective and the objective, mathematics is strangely, fascinatingly ambivalent. It maps, penetrating as nothing else can, both the nature of the observable world and that of the mind that perceives the world by means of the body and its senses. Mathematics assumes a fundamental place in science, which represents nothing else than our attempt to understand the world we experience (including our bodies and minds). Mathematics can do this because it provides a language by which we can explore, and describe precisely and profoundly, any possible set of characteristics or relationships—sometimes more accurately than words alone would allow.—C.M.

The rockets of the mind

Before experiencing some of the excitement of venturing along the intriguing frontiers of mathematical thinking, let us take stock of where we are now. We have seen that mathematics is essentially a universal language of exceptional penetration, clarity and depth. Like all languages, if it is not learned properly at the start, it may become difficult later. The language of words may be considered as a first-stage rocket for our journey into understanding. All further travel will need this basis for explanation: first, in words. Then the mathematical alphabet and grammar of operational and numerical symbols already explained in words—and with pictures, when needed—can take off by themselves and become a kind of second-stage rocket. Finally, so having gained a clear understanding of the meanings of the symbols used, we enter the realm either of real insight where discoveries are made, or else that rediscovery and retracing of great insights—which is true learning.

Teaching *v.* intimidation

Because of poor teaching, coming from inadequate, or from pedantic and obscurantist teachers who do not understand their subject sufficiently or clearly, most people become literally terrified by the word 'mathematics' itself. They say, 'Oh, I could never understand that', reflecting their childhood and teen-age traumas in this regard. The doors of their mind keep closing as their teachers first closed them. So people with enough (sometimes more than enough) intelligence to understand can be deprived of what is certainly one of the key foundations of the twentieth century's global civilization.

But this deprival need not be, and I shall seek to bridge the gap—or at least make it plausible—for even the most traumatized, perhaps even to show how to take the first steps towards wider vistas and alluring frontiers undreamed of before. I shall naturally discuss the boundary areas with which I have had most contact, and I shall follow certain guidelines. Not

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the least of these is that the central qualification of teachers in our schools must be a clear understanding of the subject-matter and the ability to explain it to those who do not understand; the teacher cannot be content with the mere possession of a collection of facts.

Some years ago, a terse but telling review which appeared in *Nature* concerning a book on mathematics (that of G. W. Watson writing on Bessel functions) made the point well, noting that clear exposition too rarely accompanies erudition. And recently, an excellent reviewer spoke out even more strongly:

> This distressing tendency to hide all geometric antecedents results from a misreading and misinterpretation of the guiding philosophy behind Oscar Zariski's work from 1937 to the present.... He never intended to throw out geometry.... The proper way to stay true to the Zariskian idea would have been to emphasize the interplay of algebra and geometry.... The book has further problems. For one thing, the notation is overbearing. For another, the theorems are stated in a maximum of notation and a minimum of [language].... Key points should be heavily emphasized via examples, geometric language and pictures to indicate what is going on.... It is a shame that the authors wrote the book in such an opaque and cumbersome style [1].[1]

It is significant that these objections, raised by a mathematician on technical grounds, are the same in principle as those levelled by the lay public against the vast majority of mathematicians. The problem of obscurantism, and often perverse hiding of direct methods, has grown so much that the mathematicians themselves are beginning to suffer. It is interesting that the review just cited appeared in a journal co-edited by the widely read mathematician, Paul R. Halmos, who himself believes in, and practises, clear exposition in both his books and the classroom.[2] May the good fight against mediocrity continue —mediocrity often masked by intimidating terminology. As Thomas Vaughan wrote in the seventeenth century, using a trenchant remark that still hits the charlatanism of pedantry: 'The mystery of their profession lies only in their terms.' With so many real and exciting mysteries facing us, we can easily dispense with the meretricious ones.

Dogma, the foe of clarity

We can be thankful that twentieth-century mathematics is graced by expositors like A. D. Aleksandrov, H. S. M. Coxeter,

1. Figures in brackets correspond to the notes at the end of the article.
2. In the same vein, another reviewer criticized a perhaps too well-known author affecting an opaque style: 'There are not enough examples', the author is incapable of motivating the reader, who 'is never told why he should be interested in certain concepts'. (*Bulletin* of the American Mathematical Society, May 1976, p. 457.) Failure to give specific examples or provide motivation is symptomatic of an author's inadequate understanding of his subject; full understanding always carries with it a rich store of examples and motivations.

Paul Halmos, Morris Kline, A. N. Kolmogorov, J. E. Littlewood, Saunders MacLane, George Polya and L. S. Pontryagin, among others. But we need more, and more in each succeeding generation, in order to provide living inspiration to successive waves of students. And it is safe to say that today's good expositors did not become so because of the present arid educational system, but in spite of it.

It is a relevant connexion here to note that dogma is always an enemy of clarity (and hence of discovery) because the intention of dogma is to propagandize or pre-judge rather than expose fact and truth to the reader or listener. Such obstructive tactics go hand in hand with obscurantism and the multiplying of neologisms in order, on the one hand, to intimidate, and, on the other, to hide a lack of novelty and even greater absence of real contribution.

Thus do human psychological problems undermine the purity of mathematics, so that we must vigilantly cultivate the antidote: high intellectual honesty and clarity.

Ad hoc axioms and over-abstraction

A contemporary historian of mathematics, himself a mathematician, has made the following remarks concerning a current trend in the field:

> Abstract algebra is marked and marred by the introduction of hundreds of new terms. Every minor variation in concept is distinguished by a new and often imposing-sounding term.... The subject has mushroomed into a welter of smaller developments that have little relation to each other or to the original concrete fields.... Indeed, most workers in the domain of abstract algebra are no longer aware of the origins of the abstract structures, nor are they concerned with the applications of their results [2].

We can profitably recall the sharp insight of Gottfried Leibniz who accused, in the seventeenth century, most university professors of possessing more knowledge than judgement and of being absorbed with trifles. Today, we are in danger of a similar scholastic theologizing of mathematics to the great detriment of human advance and understanding. Thus one of the frontiers of mathematics lies in the struggle against dead scholasticism in both teaching and teacher training.

The roots of the problem stretch back into the nineteenth century when disciplined, creative imagination (miscalled 'intuition' by too many mathematicians) began to be denigrated, to the great loss of mathematics and mathematical pedagogy. This denigration was spurred onward by thinkers too often superficial like Bertrand Russell who, though a clever writer, made not a single discovery in mathematics and often confused issues. Thus Weierstrass did not 'abolish infinitesimals', as Russell mistakenly believed, any more than caging a lion makes it disappear or consigning radio-active atoms to the bottom of the sea makes these disappear. The word 'limit', as is fast becoming evident, is actually a mask laid over extraordinarily important phenomena which we are only beginning to grasp.[1] In Russell's only book on mathematics per se (*Principles of Mathematics*) he egregiously confuses the concepts of zero and nothing. The Greeks also did this and, as a consequence, never grasped the reality of negative numbers. In Russell's case, it hindered him from conceiving the viable way to

1. Thus it is usually stated that the limit, as the variables approach unity, of the difference between the Riemann zeta function of s, and the expression $1/(s-1)$, is Euler's constant, 0.577215... · But, going behind the limit-mask and studying the actual behaviour of the infinitesimals, one derives a theorem hitherto unknown, namely that Euler's constant is also the difference between a positive number and the gamma function of its reciprocal as that number increases in size without limit. The gamma function is a well-known one, discovered also by Euler and found in any standard calculus text.

deal with infinities—a confusion that beset his theory of types, already refuted in Russell's day (with his admission) by the logician, Ludwig Wittgenstein.

Kline has made a good summary of the nineteenth-century developments [3]:

> The newly found logical structure presumably guaranteed the soundness of mathematics; but the guarantee was somewhat of a sham.... Indeed, the axioms had to yield the existing theorems rather than determine them. Rigor, as Jacques Hadamard pointed out, merely sanctions the conquest of intuition.

And before Hadamard, Oliver Heaviside (the self-taught genius of mathematical electromagnetic theory) had come to the same conclusion: rigour is too often *rigor mortis*—empty legalism instead of justice or truth.[1]

No fruitful discovery was ever made by first advancing axioms: an axiom is an afterthought. In every, far-reaching new finding in mathematics, it is the new concept or point of view which came first. The presuppositions (axioms) came later, but were presented in juggled sequence as 'foundations'—tantamount to a *de facto* falsification of the history of discovery. A colleague and friend, Marco Schützenberger (known to mathematicians for, among other things, 'Schützenberger groups'), once told me of a mathematician he knew. After he had made a new finding, the mathematician carefully rewrote his discovery so as to conceal the relatively simple way in which he had arrived at his result; then he tore up and threw away his original notes. Here the sin committed against teaching, communication and cultural transmission is obvious.

The pitfall of oversimplification

Many of these sins are committed in the name of abstraction or generalization. Let us examine closely the first, a term deriving from the Latin roots meaning to draw something from somewhere. Abstraction is thus simplification for the purpose of understanding something better. Abstraction exists for the promotion of such understanding, and it is perverse and even pathological to attempt to treat abstraction as an end in itself.

Abstraction comes in two basic varieties: (a) lumping things together and blurring, or even dissolving, distinctions because of certain common traits deemed to be of overriding importance; (b) by the same token, separating out things considered to be irrelevant, e.g. the *shapes* of objects from their *behaviour* in an *airless* gravitational field. (In such cases if we knew more about the phenomenon, and could measure it accurately enough, we would probably notice slight effects attributable precisely to gravitational field factors *screened out during a previous abstraction* as 'irrelevant' or 'nonexistent'.) It is true that, if we are confined to only limited aims or purposes, we can treat certain differences as negligible. But this should be done with our eyes open, not from being blinded by some sort of reductive abstraction.

Yet abstraction overlooks existing differences and variations, thus ineluctably introducing errors in order to simplify, and contending that this objective justifies the consequences of omission. This can be useful if we do not become so purblind in the process that we forget the existence of what we have thus neglected. The facts thereby swept under the rug often are the basis for more accurate abstractions

1. For readers far from the fray, early twentieth-century mathematics was divided into 'logicism' (according to which mathematics investigates the realm of predicated abstractions), exemplified by Bertrand Russell and his work with Alfred North Whitehead; 'formalism' (formal axiomatic theory), the school of D. Hilbert; and 'intuitionism' (which begins by considering the things most evident), whose chief proponents were L. E. J. Brouwer and K. Gödel. Since about 1960, mathematics has featured recursion theory, proof theory, model theory, and set theory.—Ed.

and, hence, more inclusive theories. Abstraction pursued for its own sake, moreover, is oversimplification for its own sake, i.e. error for its own sake—obviously a sterile, fruitless exercise:

> Abstraction many times leads to oversimplification and loss of the basic properties of the underlying structure.... Even more unfortunate is ... the production of an inordinate amount of printed trivia [4].

This unhealthy process of what I call unfruitful generalization is a distortion of reality into comparative featurelessness, a mere caricature of true or fruitful generalization. The latter always adds new concreteness, even in carrying concepts to new heights and to new levels of power. Applied mathematics often can provide an antidote to the disease of unfruitful generalization, or vapid abstraction, because applications insist that experience be reliably predicted.

Clearly, then, fruitful abstraction (which goes hand in hand with fruitful generalization) needs to be guided by keen, talented imagination that is sensitive and responsive to reality, and that brings into sharp focus subtle but effective factors otherwise difficult to perceive without the emphasis provided by creative abstraction. Such abstraction never renders things blurred and featureless; on the contrary, it introduces featurelessness into only some areas, so that key features will be highlighted rather than obfuscated in the process.

Correctives to unfruitful generalization

An example of the radical distinction between the two kinds of abstraction is provided by the treatment (unfortunately prevalent in current topology) of what are called projection operators, let us say P_1 and P_2. Usually these are defined merely abstractly, so that the square of each—the product of multiplying it by itself—is equal to itself, and so that the product of P_1 times P_2 is zero. Note, in this connexion, that the square root of a number ($\sqrt{}$) is another number whose square is the first number. Thus $\sqrt{16}$ can be $+4$ or -4 because $4 \times 4 = (-4) \times (-4) = 16$. However, few know the fruitful generalization here to an actual number ε, closely linked to $\sqrt{-1}$ (the square root of -1) as we shall see, and such that the square of ε is the number 1 even though ε itself is neither $+1$ nor -1. If we use this 'hypernumber', then P_1 and P_2 can be given form as $\frac{1}{2}(1+\varepsilon)$ and $\frac{1}{2}(1-\varepsilon)$ which, as the arithmetically minded reader can easily verify, fulfil the abstract conditions for P_1 and P_2. The point I am making is that ε, in contrast to the abstract formulation of projection operators, is an actual number—not a hypothetical abstraction—whose units are counted in a direction perpendicular to both ordinary numbers and numbers based on units of $\sqrt{-1}$. Yet so little was known about ε (because of too much abstraction of the sterile kind) that mathematicians said it had no square root [5]; this was until 1968, when I determined that ε has a perfectly good square root (see supplementary section A),[1] which interestingly enough involved the previously known hypernumber i, meaning $\sqrt{-1}$.[2]

1. The supplementary sections are denoted by capital letters, referring to the increments of information appearing at the end of this article; they provide concrete illustration of several concepts alluded to in the text or their more technical justification.
2. A complex number, $z = (a, b)$, commonly expressed as $z = a + ib$ (where a and b are real numbers), has been generalized into what is called 'hypercomplex' numbers—a notion now about a century old. If the value z is such that the hypercomplex number may have as many as four components, it is known as a quaternion. The current concept of the hypernumber differs markedly from that of the hypercomplex number in that it is not based only on i or $\sqrt{-1}$. See also pages 72-5 of the text.—Ed.

This was the first demonstration that ε and i, previously thought unrelated, shared a deep mathematical substratum.

Another danger of abstractionism of the sterile variety (besides unfruitful generalization) is that it may assume without having enough specific knowledge to assume correctly or adequately, thus leading to ultimate errors or (at best) misrepresentative or misleading conclusions. The implication, fostered by Bertrand Russell's brand of what amounts to intellectual arrogance, is that we can play superficial games with axioms, assuming any self-consistent set that we please. Yet since the findings of Kurt Gödel [6], knowing when consistency exists has become a much more complex question than it used to be—one, indeed, that may not have a ready answer. New assumptions in mathematics, furthermore, must not contradict previously *proved* statements. We thus cannot simply invent axiom games at will. We are constrained by what the great mathematician Godfrey Hardy called underlying mathematical reality. In this very deep sense, mathematics is not man-made.

It turns out to be perfectly safe to assume three different kinds of square root of -1 or i-type numbers, so that they are all mutually perpendicular. Together with ordinary numbers, these form quaternions. It is also possible to assert that there exist seven such mutually perpendicular square roots of -1, to include the previous three and form, as well, a 'closed ring' together with $+1$ and -1. That is to say, every possible product such a ring of numbers can form turns out to be one of themselves (thus keeping the ring closed). Such hypercomplex numbers are called octaves. They all stem from the first hypernumber, the square root of -1.

When assumptions are unsafe

But we cannot similarly assume more than exactly seven such square roots of -1. There is, in fact, no closed ring consisting only of ± 1 and mutually perpendicular forms of $\sqrt{-1}$ such that more than seven of these forms can exist. If we assume more than seven, we must include hypernumbers of the ε-type, where the square of ε is $+1$, instead of -1 as in the case of i-type numbers. This fact, quite unexpected, shows how unsafe it is to continue making assumptions in the abstract without the benefit of sufficient, specific knowledge. Like all unbalanced pride, arrogance about what one pleases indeed 'goeth before a fall', as in the old saying. Mathematical reality does not permit the building of such towers of Babel to go unpunished by contradiction.

This encounter with unsafe abstractionism reveals, however, the exciting project of exploring the farthest reaches of mathematical reality. This reality can be defined as the region of all those possibilities not contradicting themselves or leading to results that would introduce contradiction into the arithmetic of ordinary numbers. It was this prospect that led me, about a decade ago, to use the term hypernumber to denote those higher kinds of numbers whose arithmetics are different from (but not in contradiction with) the arithmetic of ordinary numbers.

Some historical perspective

Most likely, negative numbers based on the value -1 appeared to the ancient Greeks as hypernumbers. They regarded them as impossible, concluding that nothing 'less than nothing' could exist. In their erroneous conclusion, they confused zero, as starting-point, with absolute nothingness. It was only during the Renaissance, probably stimulated by development of banking and the dire economic reality of debits, that people realized that negative numbers represent *reversals*: that if $+1$ is a unit of progression from the departure point

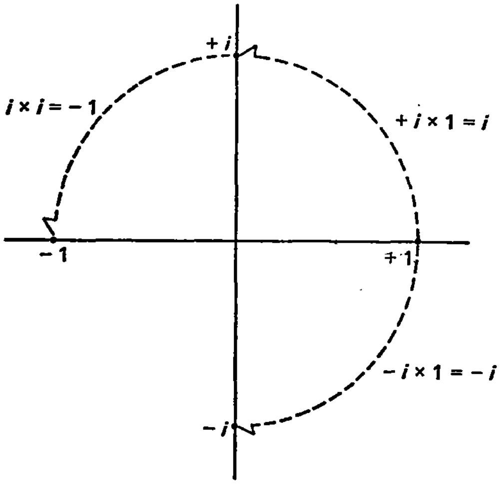

FIG. 1. How $\sqrt{-1}$ or i acts on the number 1 and on itself.

of zero, then -1 is a unit of regression therefrom.

But centuries before, in India, solutions of equations like $x^2 + 1 = 0$ were also considered impossible. This attitude persisted well after negative numbers became tolerated, the grounds for rejection being that the square of a number had to be positive. Incidentally, it can be proved formally that if $(+1)^2 = +1$, $x - x = 0$ and $x(y + z) = xy + xz$, then $(+1)(-1) = (-1)(+1) = -1$, whence it can be proved that $(-1)(-1) = +1$. But even aside from these proofs, developed considerably later, it had been long known that $(-x)(-x) = +x^2$ as necessary if arithmetic were not to be self-contradictory.

Although $\sqrt{-1}$ intruded itself during the Renaissance somewhat uncomfortably as an actual, arithmetically valid and usable number (especially in the course of Raphael Bombelli's work in cubic equations), it was not until the eighteenth century—with the findings of Leonhard Euler and Abraham de Moivre—that $\sqrt{-1}$ or i (as it came to be called) began to be recognized as neither absurd nor impossible. Nor is it even imaginary in the pejorative sense, although this appellation has persisted from days of greater ignorance.

The first hypernumber, $\sqrt{-1}$, was recognized[1] in the Renaissance, but its arithmetic did not develop until almost 300 years later, after its geometry was grasped by Caspar Wessel in Sweden in 1799. Wessel saw that these i numbers, although beginning at zero as ordinary numbers do, ran 'sidewise' or perpendicular to the line of ordinary numbers on which we find -2, -1, 0, $+1$, $+2$ and the rest. These two lines or number axes were said to cut one another, or intersect, at the point called zero. Since $\sqrt{-1}$ times 1 or $1i$ is $\sqrt{-1}$, i itself may be regarded as rotating the number length '1' through 90° of arc as in Figure 1. Similarly, $-\sqrt{-1}$ times 1 is $-i$, signifying a clockwise turn through 90°.

Wessel did not quite consciously perceive the fact of this rotation, yet in France Jean-Robert Argand did and wrote about it in 1806. But what these new kinds of numbers meant in relation to the known uses of ordinary numbers was not an easy question to resolve. As recently as 1825 one of the greatest mathematicians of all time, Carl Friedrich Gauss, wrote that 'the true metaphysics of $\sqrt{-1}$ remains elusive'.

Gaussian or complex elements

But by 1831 Gauss had published the geometry of i-numbers [8], which he called complex numbers, visualizing them as points of a meta-plane formed by the axis of ordinary numbers (or the 'axis of reals', as it is often called) and the perpendicular i-axis. Thus the number $2 + 3i$ is the point P_1 in Figure 2. Gauss wrote that, with this universally consistent

1. We introduced the term 'hypernumber' in 1966 [7]. It was then used in M. Kline's history of mathematics in 1972.

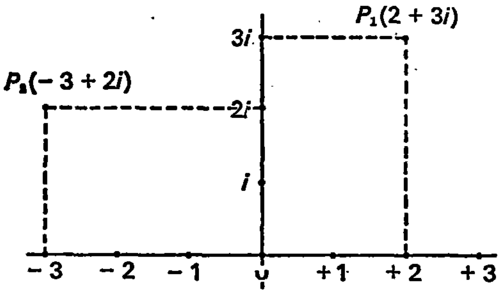

FIG. 2. The points P_1 and P_2 as the numbers $2+3i$ and $-3+2i$ where i denotes $\sqrt{-1}$.

picture, 'more is not required to admit such numbers into arithmetic'.

It is to be noted that the meta-plane, sometimes called the Gaussian or complex plane—formed by the real and i axes, should not be confused with the ordinary X, Y plane introduced by René Descartes two centuries before Gauss. In the Cartesian plane each point is represented by the two co-ordinates x, y, and not by $x+y$. In the Cartesian plane, moreover, the ordinate y times itself is y^2, whereas the square of an ordinate, say bi, is $-b^2$ in the Gaussian plane. In the Cartesian plane, the square of an ordinate can never be negative.

After Gauss's publication, it took about a decade (instead of centuries, as before) for William Rowan Hamilton in Ireland to specify the arithmetic of higher types of i-numbers: the so-called quaternions, publication of which occurred in 1843. From then on, the search for hypernumbers was consciously launched, and hence accelerated. In 1844, Hamilton's friend, John Graves, found that he could assume seven different kinds of $\sqrt{-1}$, including Hamilton's three. Two years later, Arthur Cayley, who corresponded with Hamilton and attended his lectures, worked out the arithmetic of Graves' numbers [2], the result of which is now usually called Cayley algebra (see supplementary section B). It has found applications in modern quantum theory and is the basis for Lie algebras, named after the Norwegian mathematician, Sophus Lie.

Although the germs of the notion are nascent in Hamilton [9], as I learned only in 1976 from a careful re-reading of his work, the idea of a hypernumber beyond i or $\sqrt{-1}$ was clearly set forth in the mid-nineteenth century by William Kingdon Clifford of England. He postulated the existence of the ε-type of hypernumbers I have already mentioned, such that the product of ε by itself is 1 even if ε is neither $+1$ nor -1. But Clifford never dreamed that the square root of his new number unit was related to i and had to contain two mutually perpendicular forms of $\sqrt{-1}$, thus relating the first two hypernumbers, ε and i. (See supplementary section A.)

i-numbers and quantum physics

Nor did the physicist, Wolfgang Pauli, dream (when he found his three spinor matrices in the 1920s) that he was writing in a different notation the three ε-type numbers corresponding to the three i-type numbers that were, in effect, Hamilton's elemental quaternions. (See supplementary section B.)

Not until the 1970s did my own findings show that the product of an i-number and its corresponding ε-number is a very important form of $\sqrt{-1}$ which plays a fundamental role in Paul Dirac's quantum physics (but unbeknown as such to Dirac). This product had been overlooked as well by Elie Cartan, in his trail-blazing book on spinors [10]. And although Dirac wrote a four-dimensional matrix equivalent to the product, he had no conception of the key role this form of i-number has in relating the arithmetic (hence, algebra and function theory) of both i-type and ε-type hypernumbers.

The first kind of hypernumber, based on $\sqrt{-1}$, so enabled mathematicians to forge one of the most powerful branches of mathematics, the so-called theory of functions of a complex variable. With this understanding the physics of electromagnetism, light and wave motion has developed. Similarly, the second kind of hypernumber—based on a form of $\sqrt{+1}$ or a non-ordinary square root of $+1$, unlocked the secrets of particle spin in quantum physics. Many quantum physicists are unaware that in mathematical reality their projection, spin, and helicity 'operators' are hypernumbers. And one form of the 'epsilon-type' hypernumbers plays an essential role in the Lorentz transformations used in special relativity theory.

New pioneering in hypernumbers

After reviewing the historical perspective, the natural question arises: What other kinds of hypernumber exist, and could we not try to project the direction of some of their advanced scientific applications in the light of our experience with the hypernumbers i and ε?

The answer to the first part of the question is fairly straightforward. Each kind of hypernumber has its own characteristic arithmetic. As we have seen, in ordinary arithmetic, the product formed by multiplying a number (positive or negative) by itself must be positive. But in i-arithmetic, it is basic that a pure i-number multiplied by itself must yield a negative product. And in ordinary arithmetic, the product of two non-zero numbers cannot be zero, whereas in epsilon arithmetic it is easy to verify that neither $1 + \varepsilon$ nor $1 - \varepsilon$ is zero and yet that their product is zero.

The rules of ordinary arithmetic are finite in number, hence their denials or abrogation must also be finite in number. Therefore, the number of different kinds or types of hypernumber is also finite.[1] We have shown that there are most probably only eight types, and hence only nine types of number altogether, including ordinary numbers—and ten types if we regard zero (together with its reciprocal, which is infinity) as a special class or type, which there is a good reason for doing. There is one type in particular (see supplementary section C) beyond ε and i, which I have called w; there is reason to believe that this will play a vital role in the further development of quantum physics by helping to avoid some unwanted infinities.

The essence of the concept of a hypernumber does not lie in the domain of mere mathematical novelty or strangeness; it is much more fundamental. Simply by the adding of the first hypernumber, $\sqrt{-1}$, to the mathematical repertoire, a whole new realm of algebra and function theory was opened, which nothing else could have done. Similarly, adjoining the second hypernumber, ε (a proper form of $\sqrt{+1}$), immediately enlarges algebra again and brings function theory far beyond Hilbert or Banach spaces. In this sense, hypernumbers may be said to be at the very core of mathematics, and they provide a powerful approach to new frontiers.

Obstacles: unfamiliarity and prior conditioning

Let it not be imagined that the search for hypernumbers was straightforward, without missteps and even painful backtracking in order to refind the trail. (It took Hamilton fifteen years to learn how to perform multiplication with his quaternions.) We have noted how Cartan and Dirac overlooked the structure and deep relation to ε-numbers of a very important form of the square root of -1 (which

1. There may be, however, endless *sub*-varieties of a *given* type. Thus (a) there is an infinitude of i-type units, but (b) they all share a basic arithmetic in that their squares are all -1, the product of any number of them can never be zero, and the points representing their real powers form a unit circle.

I shall mention presently). Gauss's dictum that 'the metaphysics of $\sqrt{-1}$ is elusive' still held good.

It is generally not recognized how the most famous mathematicians made errors (sometimes to be corrected by themselves, and sometimes not). This applies to great names, such as those of Cauchy and Euler, as well as to twentieth-century lights such as Volterra and Birkhoff [11]. To err is human, for that is how we learn; the errata, even if they appear in the publications of the most prestigious mathematical societies, belie the (unrealistic and affected) stance of some who contend that a published error of fact or concept is either impossible or an unforgivable blemish. It is safe to say that a great number of works which have never suffered a published error were also trivial and not fundamental.

In discovery, one is traversing hitherto unfamiliar realms, domains in which training and conditioned expectations can be obstacles that may deter one seriously. Even the undoubted genius of Hamilton was stopped for fifteen long years because his early training had told him that x times y always had to be the same as y times x. Since this did not apply to quaternions, his solving of the question 'How to multiply them?' was enormously delayed *because of the unfamiliarity of new possibilities rather than inherent complexity in them.*

This important phenomenon in the psychology of discovery is also the reason that it takes many times longer to develop a radically new concept than it takes to explain or teach it (to someone of comparable intelligence). My own experience with hypernumbers bears this out fully.

I still recall how first, after reading that the number ε could have no square root—and deeply sensing this to be untrue—I sought its square root on the top of the base of an imagined right cone, with its vertex at the origin of all the number axes at zero. But the idea did not work. It was only later, when I tried a *four*-dimensional cone, that it worked. And yet it was algebra which led me to the geometrical solution. I saw that the product εi could not be ± 1, $\pm \varepsilon$, nor $\pm i$; hence, it had to be a *fourth* number axis, perpendicular to the three others. Thus the square root of ε required a four-dimensional space for its geometric representation.

With geometry furnishing the square root, $\pm \frac{1}{2}(1 + \varepsilon - i + \varepsilon i)$, I noted that εi is the same as $i\varepsilon$ and that its roots behave like the root of i itself. So I called εi 'i_0' and thereby specified an important form of $\sqrt{-1}$, for i_0 times any quaternion always yielded an ε-number as product. I used algebra, then, to gain the formula for any root of ε, and not only its square root (see supplementary section A).

The algebra-geometry analogy

During the entire process of discovery, geometry and algebra zigzagged. Each was used to advance the other's penetration, much as one alternately uses left and right arms in climbing a steep incline. My experience with hypernumbers had made me see, more and more, that geometry and algebra are not separate but essential and isomorphic to one another: every algebraic statement has a geometric analogue, and vice versa. It should be increasingly apparent to the reader what a sterile and futile affectation it is to try to express geometry in only algebraic terms, or to attempt to make dogmatic separations between the two approaches. Fundamental understanding requires both.

The square root of i needs only a plane to represent it. A plane, being formed by only two perpendicular lines, is (like the surface of a sheet of paper) only two-dimensional. But the square root of ε requires a space generated by, not two, nor three, but four mutually perpendicular lines intersecting at a common point—some-

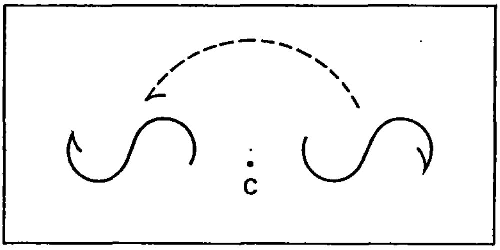

FIG. 3 (a). Simple rotation of 180° in the plane about centre C.

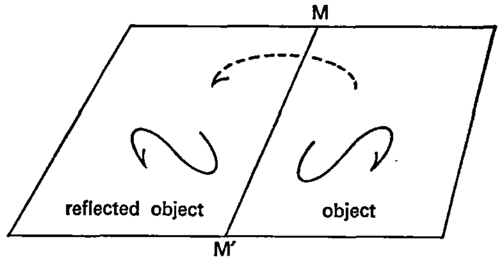

FIG. 3 (b). Reflection through the line M–M. Unlike rotation, reflection involves a 180° rotation out of the plane and back again.

thing our three-dimensional imaginations cannot completely visualize.

Algebraically, these implications are simply part of the brute facts comprising numerical relationships, not further to be explained. The geometry involved, however, can lead us to a deeper understanding of this phenomenon. The hypernumber *i* needs only a plane for visualization because, as it is multiplied by itself, it rotates in a plane as does a unit radius when a circle is drawn. But the hypernumber ε involves *reflection*, as 'matrices' will show (see supplementary section D). This implies a rotation *out* of the plane and back again (see Fig. 3). Note that, though in each case there is rotation of 180°, the simply rotated object is not the same as the reflected object. Nor can they be brought into congruence merely by sliding or rotating them on the plane.

Planes, reflections, and spin

Chirality (right- or left-handedness), which plays an important role in twentieth-century chemistry and physics, thus concerns reflection rather than rotation. It is clear that in order to turn a right hand into its reflected version (a left hand), more is required than sliding or rotation in tri-dimensional space. It can be shown that a right hand would be changed into a left hand if it were rotated 180° *out* of our triple dimensional space into four-dimensional space, and then back into our space again—just as the S-shaped form in Figure 3 (b) is rotated 180° out of the two-dimensional plane, and back. Even here, three-dimensional rotation does not suffice as it does not leave the same side of the surface facing upwards, as true reflection does.

Therefore, because ε deals with reflections and not only with simple rotations as does *i*, its operations demand geometrically a four-dimensional space, whereas the simple, rotational character of *i*'s operations demands only two-dimensional space. Even though solid or three-dimensional objects can rotate, the basic paradigm of the operation of simple rotation needs no more than two dimensions. But the basic paradigm of reflection requires four dimensions if we are to understand how reflection can change a right hand into a left hand, and vice versa—without turning the hand inside out.

It is well known in quantum physics that operations equivalent to those produced by ε-numbers play an essential role in both electron spin and neutrino 'helicity', both terms implying a kind of spin. As the kinematic geometry of epsilon has told us, however, it is now clear that this spin is more like successive rotation, through a four-dimensional space and then back into ours, rather than an ordinary, three-dimensional spinning. As of this writing, it is realized among physicists that such 'spin' is not ordinary; but ε clarifies what it is.

The trail ahead

I would like now to survey certain new frontiers of thought. Because of the brevity necessitated by limitations of space, I shall make unavoidable reference to some fairly technical concepts (but I shall avoid details) [12]. The ideas are so vivid and exciting, however, that the reader may enjoy some of the flavour of the pioneering and exploratory experiences making such concepts attainable and, afterwards, applicable to human problems and the human condition.

Zero and infinity

These two ideas are intimately related, yet ill understood. They are related because zero represents the ultimate condition of the increasingly smaller and smaller, and infinity that of the ever larger and larger. Although all infinitely small quantities are zero with respect to finite numbers (like microscopic protozoa to the naked eye), they need not at all be so with respect to each other (there are small and large protozoa). Thus $6x$ becomes zero when x is infinitely small, and so does $3x$. But the ratio of these two zeros is still the ratio of $6x$ to $3x$, namely 2. Similarly, when x is infinitely great, both $6x$ and $3x$ are also infinite. But the two infinities are not the same; their ratio, again, is 2.

Thus zero or infinity is not so much a simple number as each is a whole class (more technically, 'ring') of numbers, infinitely small or infinitely large. But the product of a member of the zero class multiplied by a member of the infinite class may be a finite number. Thus if the infinite number M is produced by x when x becomes infinitely large, and the infinitesimal or zero-type number z is produced by $1/2x$ as x becomes infinitely large, then M times z is $\frac{1}{2}$, a finite number. But this need not be so. If M' is produced similarly to M, but by x^2, then the product of M' and z is infinity. On the other hand, if z' is produced similarly to z, but by $1/2x^2$, then the product of M and z' is zero.

This means that one may perfectly well use 0 and ∞ in arithmetical operations, including division and multiplication, provided that one makes clear which specific members of the classes of zero or infinity one is using. There is no need to retreat into arbitrary, and logically unjustified, proscriptions against operating with zero or infinity.

Indeed, just as one can multiply a certain zero by a certain infinity (and obtain a certain finite number), similarly an *infinity* of zero-type numbers may add to more than zero (although a finite number of zeros will yield only zero). Take, for example, the series

$$\frac{1}{n} + \frac{1}{n+1} + \frac{1}{n+2} + \ldots + \frac{1}{n+n} = S_n.$$

It is provable that S_n remains greater than zero as n increases, even if it becomes infinitely large (see supplementary section E). In fact, S_n becomes the natural logarithm of 2, i.e. the specific finite number which is given approximately as 0.693. (This result can easily be verified on a small, electronic calculator.)

Divisors of zero and hypernumbers

With ordinary numbers, if the product of x and y is zero, then either x or y is zero, or both of them are. If x and y are hypernumbers, however, this need not hold. We showed only recently that zero-th powers of divisors of zero cannot be 1, nor are their reciprocals ever equal to their first negative powers (as with ordinary numbers) [12]. The arithmetic of divisors of zero necessarily involves, finally, divisors of infinity and is non-associative (see end of supplementary section B). This makes matrix algebra only 'almost associative', instead of fully associative as hitherto believed.

All algebras are based on arithmetics, and all distinct arithmetics operationally define distinct hypernumbers. Just as arithmetic is richer in theorems than algebra, so hypernumber theory includes more than ring theory. I have already alluded to rings: a ring is an abstractly defined set of objects such that the product of any two of its elements is also a member of the set.

One-to-one correspondence

One-to-one correspondence between the members of two sets of numbers proves the equality of the two sets only if they are finite sets. Since an infinite set is by definition non-exhaustible, a mere matching or pairing between members to any finite extent—however great—can never prove equality of membership. What may be established is that each set has a 'threading rule' or rule of selection so that members can be chosen without repetitions from each set. Two such finite sets may or may not be equal.

Thus the set of prime numbers is infinitely smaller than the set of all natural integers; indeed, the ratio to n of the number of primes less than n, as the number n increases without limit, approaches zero. Yet the two sets can always be matched or paired to the extent desired. Thus set theory[1] alone cannot provide an adequate measure of the cardinal comparison between two infinite numbers.

Fractional dimensions

Fractional dimensions are topological dimensions (and not merely measures of content), the dimension of space being one less than the number of points minimally needed to define the boundaries of an enclosed segment of that space. Thus at least three points are needed to bound a plane or two-dimensional area; two to bound a one-dimensional length; at least four to determine an enclosure (in this case a tetrahedron) in ordinary or tridimensional space, and so on. But what of 'half-dimensional' or even 'two-and-a-quarter dimensional' space? It turns out that fractional dimensions can be tangibly and consistently defined, and that they possess concrete geometries that are intimately related to the physics of quantized fields [13].

Anti-numbers exist

Anti-numbers are finite numbers, but 'on the other side of infinity', such that anti-zero is infinitely removed from both zero and infinity, including the infinities of all hypernumbers.

This is one of the new frontiers still in the process of traversal. The anti-number concept is rich and mathematically and ontologically very productive. But its subtle complexities are abundant, and remain to be worked out explicitly. In particular, the paths of interaction and self-interaction for the hypernumber v (which can pass from the ordinary or 'recto realm', as it were, to the anti-realm of number and back again) remain to be specified. Brief mention of the problem was made in 1972 [14] and the problem is still in process of resolution. Yet, after all, this is the life blood of exploration. If all were solved and nicely known, discovery would be dead and familiarity then would sooner or later breed boredom, even if not contempt, for human beings, unlike ants, have the happy faculty of becoming bored with too repetitious patterns of activity and expectation. So long live the as yet Unknown!

1. Set theory, known in essence since Galileo and developed by Georg Cantor (1845–1918), is considered to be one of the greatest achievements of mathematics during the nineteenth century.

We have now come to a halt in our long journey, only to find that we are facing an endless vista of new challenges. Pushing back the frontiers of mathematics promises not only to deepen further our understanding of the natural sciences, but to help us grasp better the constitution of our consciousness and its very texture. Mathematics, like the magical pentagon (the first polygon with this property), can extend infinitely—without or within (Fig. 4), suggesting an infinite macrocosm and microcosm to explore. □

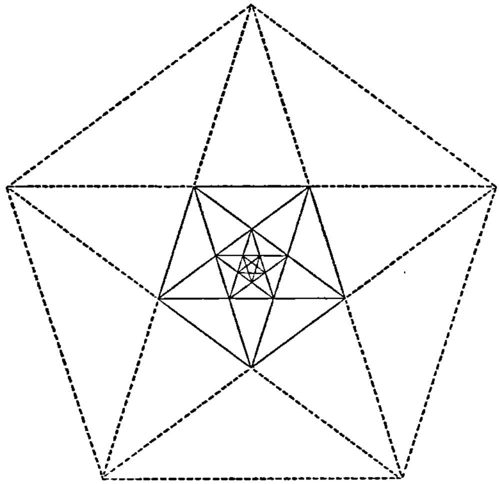

FIG. 4.

The pentagon is the first closed shape, among those of three or more sides, to be able to extend itself infinitely, both without and within, by forming stars.

Supplementary sections

A. On the square root of epsilon and related matters

With epsilon defined by $\varepsilon^2 = 1$, $\varepsilon \neq \pm 1$, when investigating a four-dimensional cone of 90° vertex angle, I found in February 1968 that $\sqrt{\varepsilon} = \pm \frac{1}{2}(1 + \varepsilon - i + i_0)$, where $\varepsilon i = i\varepsilon = i_0$. Actually the i and ε here are i_n and ε_n, where the subscripts agree and exceed zero. For $n \leqslant 3$, i_n and ε_n can be represented by matrices. If the 4-cone mentioned above has its vertex at the origin and has unit slant height, with its profile intersecting the axis of ordinary numbers, as well as the i-axis, the ε-axis and the i_0-axis (note that i_0 is perpendicular both to i_n and ε_n as well as to ± 1), then the circle of its base contains all and only the points representing the real powers of ε, or ε^k. Specifically I found that $\varepsilon^k = \cos^2 \pi k/2 + \sin^2 \pi k/2 - \frac{i}{2}(1 - \varepsilon) \sin \pi k$. It is easy to see that if $k = \frac{1}{2}$ we have the positive square root of ε first given.

Unlike i, the real powers of ε cannot be written as real exponentials of ε. That is, $\varepsilon^k = e^{\theta\varepsilon}$ is not soluble for real k and θ; whereas $i^k = e^{\theta i}$ yields $i^k = e^{\pi k i/2}$ and hence $\theta = \pi k/2$ as the principal value. During this same period I also proved that $(\cosh\theta + \varepsilon\sinh\theta)^k = e^{\varepsilon\theta k} = \cosh k\theta + \varepsilon\sinh k\theta$, which was not known even in 1968 [5] and which enormously simplifies hyperbolic geometry. The awkwardness of work up to 1968 in this regard easily demonstrates the point.

B. Hamilton's and Cayley's numbers

Hamilton's elemental quaternions i, j, k or i_1, i_2 and i_3 can be represented uniquely by [see D, below] the matrices $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$, $\begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$, and $\begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$ respectively, where $i \equiv i_1$. This representation is unique because $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ is the only possible 2×2 matrix that rotates the number length $+1$ by 90° counterclockwise in the plane as required by i or $\sqrt{-1}$ in simplest form. Note that although i_0 is commutative with i_1, i_2 and i_3 and though i_1 is not commutative with i_2 and i_3 (since $i_1 i_n \neq i_n i_1$ where n is 2 or 3), yet i_0 is not simpler than i_1; for the matrix of i_0 is $\begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix}$, which represents a rotation in 4-space and not on the Gaussian plane.

That fact is easily seen since i_0 requires a 4×4 matrix if all the matrix elements are to be real. Hamilton was confused about i_0 versus i_1, and the confusion persisted through Elie Cartan and Paul Dirac, until we specified the matrix forms of both in the early 1970s and the distinction between the two hypernumbers.

When we come to i_4, i_5, i_6 and i_7, which are needed in the arithmetic and algebra of Cayley, we can show that none of these can be matrices since their multiplication is in general not associative; that is $a(bc)$ no longer necessarily equals $(ab)c$. The Cayley arithmetic is easily defined by $i_1 i_2 = i_3$; $i_1 i_6 = i_2 i_5 = i_3 i_4 = i_7$; $i_3 i_5 = i_4 i_2 = i_6$; and $i_1 i_4 = i_5$. In any of the foregoing equalities, if $i_a i_b = i_c$ then $i_b i_c = i_a$ and $i_c i_a = i_b$. Also $i_n^2 = -1$ and $i_n i_m = -i_m i_n$. Note that $(i_1 i_2) i_5 = i_3 i_5 = i_6$; but $i_1(i_2 i_5) = i_1 i_7 = -i_6$. Hence multiplication is non-associative. Only $i_{1,2,3}$ are matrices; the rest are not.

Also note that although i_4 and i_5 cannot be matrices (since matrix multiplication is defined as associative), yet $i_4 i_5 = i_1$ and i_1 is definitely a matrix. So the product of two non-matrices can be a matrix, indeed must be in Cayley arithmetic; whereas the product of a matrix and a non-matrix must be a non-matrix (here the zero or null matrix is excluded as a factor).

Considering this fact closely we were able in 1973 to enunciate the concept of a *bimatrix* (defined as a pair of separated matrix domains connected by certain rules) and soon after to show that Cayley arithmetic and algebra could be completely solved in terms of bimatrices, since the product of two bimatrices could be a matrix [13].

The rules are as follows. If A and B are matrices then A/B is a bimatrix, and, where $i \equiv i_1$, we have $i_4 = i/$; $i_5 = i/i$; $i_6 = -i_2/i$; and $i_7 = i_3/i$. The rules are: $(/B)^2 = /B^2$; $/1 = 1$ and $/-1 = -1$; $(A/B)^2 = -A^2/B^2$; $(A/B)(/B) = -A/B^2$; $(/B)(A/B) = A/B^2$; $A(/B) = A/B$; $(/B)A = -A/B$; where $A \neq C$, $(A/B)(C/B) = AC/B^2$; $(C/B)(A/B) = -AC/B^2$.

Only matrix algebra is needed to accommodate the ring based on i_0, i_1, i_2, i_3, ε_1, ε_2, and ε_3, where $\varepsilon_1 = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}$, $\varepsilon_2 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ and $\varepsilon_3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$. Note that $i_n \varepsilon_n = \varepsilon_n i_n = i_0 = \begin{pmatrix} i & 0 \\ 0 & i \end{pmatrix}$, where $\varepsilon_{1,2,3}$ are the Pauli spinors of quantum physics.[1] It turns out that the helicity operator for the neutrino in quantum physics is simply ε_2 and that the two projection operators are most simply represented by $\frac{1}{2}(1 \pm \varepsilon)$. Both are idempotent (remaining unchanged when multiplied by themselves) as they should be, and $(1 + \varepsilon)(1 - \varepsilon) = 0$ even though none of the two factors is zero. Note that $[\varepsilon(1 + \varepsilon)](1/1 + \varepsilon) = 1$ but that $\varepsilon[(1 + \varepsilon)(1/1 + \varepsilon)] = \varepsilon$. Thus the arithmetic of divisors of zero is not associative. This is a new finding.

1. Now, with bimatrices. I have specified the new 'M-algebra' (for Meta-Cayley)—a 16-element ring beyond octaves or Cayley algebra, and consisting of ε_0 or 1, ε_1 through ε_7, and i_0 through i_7, with consequent relevance to future quantum physics.

The new concepts of *power orbit* and *exponential orbit* prove very useful in hypernumber investigations.

Every unit hypernumber, u^1, can be considered as u to the first power or u^1, u times u or uu as u^2, u times u^2 (or uuu) as u^3, and so on. For a class of very important hypernumbers it is true that $u^n = 1$, where n is the least integer greater than 1 that will satisfy the equation. Thus $i^4 = 1$ and $\varepsilon^2 = 1$. For all such hypernumbers it can also be shown to be true that $u^0 = 1$, and the passage from $k = 0$ to $k = n$ takes the function u^k along a closed path or orbit, consisting of all the values formed by raising u to the kth power as k proceeds from 0 to n. This path we call the *power orbit* of u. Negative values of k traverse their orbit in the opposite sense.

The exponential orbit is similarly defined as the path traced out by the function $e^{\theta u}$ as θ takes on successive real values. In the case of the hypernumber i, $e^{\theta u} = i^k$ can be solved for $u = i$, and in fact then $\theta = \frac{\pi}{2}(k \pm 4m)$, where $m = 0, 1, 2, 3, 4, \ldots$. Since $m > 0$ implies more than one orbit traversal, we can confine ourselves to a single traversal and write $\theta = \pi k/2$.

But for epsilon, the power and exponential orbits are not identical as is the case with i. We now have $e^{\theta\varepsilon} = \cosh\ \theta + \varepsilon\ \sinh\ \theta$, whereas $\varepsilon^k = \cos^2\ \pi k/2 + \varepsilon\ \sin^2\ \pi k/2 - (i/2)\ (1 - \varepsilon)\ \sin\ \pi k$. In the case of i, both $e^{\theta i}$ and i^k were circles, indeed the same circle: $x^2 + y^2 = 1$, in Cartesian form. But, though ε^k represents a circle, it is a circle oriented in a space of four dimensions, whereas $\pm\, e^{\theta\varepsilon}$ does not represent a circle at all, but a rectangular or equilateral hyperbola, with Cartesian form $x^2 - y^2 = 1$. Similarly, $\pm\, \varepsilon e^{\theta}$ corresponds to $x^2 - y^2 = -1$.

In the case of the hypernumber w, it is defined by the equation $(\pm\, x)^6 = 1$; $w^2 = -1 + w$. Thus w is not the same as $i^{2/3}$ since the power orbit of $i^{2/3}$ would be a unit circle, but the power orbit of w is not. Just as the real power orbits of both i and ε are circular, that of the hypernumber w is elliptic.

Thus it can be proved that, for all real values of θ, $e^{\theta i}$ or $i^{\pi k i/2}$ denotes a circle in the Gaussian (meta)plane. Likewise ε^{θ} forms a circle in a meta 4-space. The real powers of w, or w^{θ}, however, form an ellipse, with Cartesian equation $x^2 + xy + y^2 = 1$; and the powers of $-w$, or $(-w)^{\theta}$, form another ellipse of same size and shape but with axes perpendicular to the first ellipse and Cartesian equation $x^2 - xy + y^2 = 1$.

It can be shown that $w^2 = -1 + w$ and hence $w^3 = -1$ and $w^{1} = (1 + w)/\sqrt{3}$. Similarly $(-w)^2 = -1 - w$ and although $(w)^3 = -1$, yet $(-w)^{1/2} = (1 - w)/\sqrt{3}$.

D. On matrices

If a point by any combination of rotations or translations (including stretching or shrinking of distance), changes its position given by, say, its x and y co-ordinates on a plane, or by its x, y and z co-ordinates in three-dimensional space, then the way the co-ordinates of its new position are formed from those of its old position is called the matrix of this change or transformation. Such matrices are found to possess deep affinities with the most elementary varieties of the first two kinds of hypernumber: the i-type and the ε-type. Thus if x, y is the original position, and x', y' the new position, and if $x' = 0x - 1y$ and $y' = 1x + 0y$, the matrix of the transformation is written as $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$, the $0, -1$ being taken from the first equation and the $1, 0$ from the second. This is the matrix for i_1, the simplest form of $\sqrt{-1}$ as a 90° counter-clockwise rotation in the plane.

It had long been thought that matrices like $\begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix}$ had no square (or cube) roots. However, we recently showed that such matrices, comprising a special or nilpotent class of what are called singular matrices, do have roots, but these exist in the neighbourhood of infinity. Thus the square root of $\begin{pmatrix} 1 & -1 \\ 1 & -1 \end{pmatrix}$ is $\begin{pmatrix} M + z & -M \\ M & -M + z \end{pmatrix}$, where M is an infinite number, z is an infinitesimal, and $2Mz = 1$. The explicit functional forms of M and z can be obtained by hypernumber treatment. It is a great mistake to believe, however, that the subject of hypernumbers can be exhausted by matrices.

The theorem in question is proved by using the logarithmic derivative of Gauss's factorial function or of Euler's gamma function. In its more general form:

$$\lim_{n \to \infty} \frac{1}{n} + \lim_{n \to \infty} \frac{1}{n+1} + \lim_{n \to \infty} \frac{1}{n+2} \cdots + \lim_{n \to \infty} \frac{1}{n+nk} = Ln(k+1),$$

where *Ln* denotes the natural logarithm or logarithm to the base $e (e = 2.71828$ approximately). This infinite series, all of whose terms are zeros, may have a finite sum, and is a new result. □

Notes

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6. K. Godel, *Monatshefte f. Mathematik u. Physik*, vol. 38, 1931, p. 173.
7. C. Musès, *Ann. New York Acad. Sci.*, vol. 138, 1967, p. 660, 901. Here appeared for the first time the term 'hypernumber', taken up thereafter by the mathematician, Kline, *op. cit.*, p. 782 et seg.
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11. F. Gantmacher, *The theory of matrices*, vol. I, p. 145–8, New York, N.Y., Chelsea Publishing Company, 1959, 1960.
12. C. Musès, 'Fractional dimensions and their experiential meaning, with some new theorems, proved on divisors of zero' *J. Study of consciousness*, vol. 5, no. 2, 1972–73, p. 315–29. Since then, we have shown that the product/modulus law in its usual (positive indefinite) statement is equivalent to stating that the divisors of zero are absent.
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Happenings in chemistry

The Nobel Prizes for chemistry awarded in 1975 and 1976 have served to underline the importance of laboratory developments in biochemistry and molecular biology, in the chemistry of interactions and interfaces, and in the chemistry of materials. Some of the uses of these research results, particularly as they apply to man and society, are reviewed briefly.

Immunochemistry

Working together in the field of immunochemistry, chemists and biologists have developed models of the tridimensional molecular structure of the functional end of antibody molecules, the antigen-binding fragments or 'fabs'. Fabs are the molecular portions which intercept specific disease agents when these enter the bloodstream. A small peptide, for example, has been synthesized which seems to cancel the allergic response to such environmental factors as the pollen causing hay fever.

Chemists have also established the amino-acid sequence of a ragweed allergen (*Ra5*), one of five known to cause the signs and symptoms familiar to anyone who suffers from hay fever.

A mixture of hydrogen (97.5 per cent) and oxygen (2.5 per cent) under eight atmospheres of pressure has been used for the respiratory needs of mice affected with skin cancers. After ten days of treatment, the malign tumours turned black, shrank, or dropped off the test animals. These tests were repeated successfully, in parallel with two control groups—one of which breathed normal air and the other a mixture of 97 per cent helium and 3 per cent oxygen. The cancers of both these control groups continued to grow. The current theory to explain the test results is that the high-pressure hydrogen may slow the rates of metabolism and respiration of cancer cells, thus inhibiting the growth of tumours. This process may lead to an enhancement of the animal body's immune system, i.e. its ability to recognize and reject foreign cells.

Laser chemistry

A xenon laser and a krypton laser have been used to raise the concentration of uranium-235 from its natural abundance of 0.7 per cent to the 3 per cent required in many reactors. The process used was a two-step photo-ionization technique to separate isotopes.

Sulphur-34 (^{34}S) is a non-radio-active substance useful as a trace element in both food-chain cycles and in medical diagnosis. ^{34}S has been enriched from 500 to as much as 3,300 per cent. This represents a cost of isotope enrichment approximately 1/2,500th of what it would be when a laser is not used.

A neodymium glass laser has been used to study the conversion of light energy into chemical energy in the photosynthesis of a strain of bacteria *(Rhodopseudomonas sphaeroides)*, specifically the time elapsed during the actual transfer of energy. The transfer is determined by the bleaching of chlorophyll, a process which in this case was determined to require between 6 and 12 picoseconds.

What's new in polymers

A new kind of giant-molecule polymer is the family of phosphazenes: long chains of alternating atoms of phosphorus and nitrogen. Stable forms of this family include rigid plastics, rubbery elastomers, films and coatings (both waterproofing and flame-retardant), and expansible foams. Phosphazenes with amino-acid esters along their backbones, biodegradable, could prove to be useful in reconstructive surgery.

Pre-treated whole-grain starch added to polyethylene makes this polymer, when buried, break down because of the action of moisture, bacteria and fungi on the biodegradable compound. Result: carbon, hydrogen and oxygen pass into nature as carbon dioxide and useful humus.

Combating cancer

Besides the amelioration of the immune system as reported in the case of skin cancers on mice (third paragraph, above), another recent discovery in chemistry concerns cancer detection. New analytical methods, using gas-liquid chromatography and cation-exchange chromatography, can determine with precision abnormal levels of polyamines present in the urine of patients afflicted with advanced malignancies. This is a discovery in coincidental correlation: biochemical clues to distinguish patients with cancer from those in whom the disease is absent.

How diabetes works

Glucagon—mainly a pancreatic hormone—and somastatin —coming chiefly from the hypothalamus—are proving to be new clues to the functioning of diabetes, as these hormones have a role in the regulation of glucose metabolism. Although both Chinese and Swiss specialists have succeeded in the 'unambiguous' synthesis of insulin, the process is so complex that it may never be used commercially to manufacture insulin intended for human use.

Diabetes mellitus, to use its medical name, is the consequence of malfunction in the metabolism of the carbohydrates, fats and proteins ingested by a diabetic patient. His glucose is not transformed into fatty tissue and muscle but is accumulated in the blood and then excreted in the urine. Some secondary effects include arteriosclerosis, cataracts and a type of blindness called retinopathy. Diabetes is normally controlled by injections of the pancreatic hormone, insulin, or by drugs consumed orally to induce the pancreas to manufacture a higher level of insulin than is usually available to the patient. Better understanding of the regulatory roles of somastatin and glucagon, therefore, may well spell good news for the diabetic.

New efforts in insect control

Synthetic pheromones (sexual lures) are now being used against several strains of cockroach and the highly destructive cotton weevil (*Authonomus grandis* Bohemian). The pheromones, which are olfactory acids, are utilized in such a way as to lure the male of a species into a trap from which he cannot extricate himself. The consequence is that the propagation of the species is severely curbed.

Innovation in food

Making up for foods lacking certain amino-acids, such as lysine, methionine and tryptophan, has long been a challenge to nutrition chemists. Certain mutant strains of bacteria, it has been found, increase considerably the lysine content (for example) of yogurt, buttermilk, cheese, pickles and sauerkraut or the famous *kimchi* of Korean cookery. The same effect can be had, incidentally, with corn silage destined for consumption by bovines and other animal stock.

A protein recently synthesized in Japan, plastein, contains all the most desirable amino-acids, including lysine, methionine and tryptophan. The research leading to the development of plastein resulted from efforts on the part of the Japanese food industry to make products derived from the soybean less farinaceous than usual.

Pollution

From Japan also comes a technique to suppress much of the nitrogen oxide pollutants present in industrial smoke. Japanese industry is using ordinary activated charcoal, soaked in ammonium bromide, to remove, at 100 C, as much as 80 per cent of the nitrogen oxides expelled by industrial flues. At 130 C, all these pollutants are removed.

Developments in energy

Calcium hydroxide, serving as a catalyst, is reacted with hydrogen or steam, or both, in order to convert bituminous coal into synthetic natural gas.

In electrochemical energy generators (fuels cells), the chemical energy of the fuel is transformed directly into electrical energy with greater efficiency than in the case of other energy converters. The chief advantage of fuel cells is their high degree of efficiency—from 1.5 times to twice the efficiency of traditional power plants or of those likely to be developed. Other advantages are high co-efficients of specific capacity, simplicity of construction, the absence of moving parts, the absence of noxious emissions, silence and reliability. Although the problem of fuel cells is not new (it has been studied for more than a century), no significant progress had been possible because of various scientific and technological obstacles. It is only since about twenty years ago that the industrial manufacture of fuel has become a possibility. □

To delve more deeply

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Learning processes in man, machine and society

Mircea Malita

Deciphering the learning mechanism which exists in man remains to be solved. Associationism has long been the most acceptable theory to unravel the mystery; the mechanistic pattern of inferred stimulus-response is easily rendered mathematically. Current global problems call for exploration, however, of the higher learning processes involving self-organization. Ecology, for example, invites the question: How do societies learn? Research should focus on the transdisciplinary processes of learning which could become the next key concept in the science of man.

Nearly three decades have passed since the publication of Norbert Wiener's *Cybernetics* [1],[1] acknowledging a new direction of research as one of the characteristics of the present scientific and technological revolution. By providing a common framework to a wide range of phenomena in the field of control and communication—ranging from biology to machines and to social science—Wiener created concepts which dominate in today's science. His work has brought about a shift from scientific explanation based on energy to one based on signal. As Wiener explained it,

> We are beginning to see that such important elements as neurons, the atoms of the nervous complex of our body, do their work under much the same conditions as vacuum tubes, with their relatively small power supplied from outside..., and that the bookkeeping which is most essential to describe their function is not one of energy.... In short, the newer study of automata, whether in the metal or in the flesh, is a branch of communication engineering....

This central idea of cybernetics[2] has left its mark on the technological civilization which has been thriving over the past three decades. This is less of a high-energy revolution than one would think, however, since we continue to use preponderantly classical types of energies to accomplish work. We have not yet pushed the explanation of the world beyond the basic theories on matter and energy devised before this period. But what is pre-eminently new is the emergence of information science: decision theory, operational mathematics, control methods, automation techniques, and computers themselves.

The substantial increase in industrial efficiency during the same period has resulted not so much from changed substance as from rearrangement. The key terms in the scheme have been structures, organization, entropy, optimal processes, and the allotments and distribution satisfying maxi-

1. Numbers in brackets correspond to the references at the end of this article.
2. A. Chandor (ed.), *A Dictionary of Computers*, Harmondsworth, Penguin, 1970. Cybernetics: the study of the theory of control systems with particular regard to the comparisons between machines and the nervous system of animals and men.

■ Mircea Malita

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mal and minimal criteria. The trend is far from exhausting its potential. Although some specialists think that the cycle will draw to a close and a subsequent period would again bring energy and materials to the fore, there are indications that a second generation of problem analysis (or *problématique*) is already emerging in the form of system theory. System theory seems to be tackling the fundamental problems originally dealt with by the cybernetic revolution. What, then, has been the dominant concept of the first phase?

Self-regulation, adaptation, learning

Let us go back to the basic mechanism of feedback, by which a system corrects its reactions according to signals received from outside. We find this in the thermostat, maintaining constant temperature within a room or building, and the various homeostases of the body that maintain the essential parameters of the chemical composition of blood, for example, within a certain range of variation. This transactional relation of the body to its surroundings, through which a low-energy signal from outside the body can be converted into a high-energy response, is a mechanism for self-regulation.

If we take the term 'learning' in its broadest sense—as a change in behaviour as a result of the acquisition of information—then, considering the action of feedback which reduces deviations from the correct response, we have the simplest process governing the relations between systems and their environment; this, in turn, introduces higher classes of learning.

In order to understand the difference between (a) self-regulation, (b) adaptation, and (c) learning, we must re-visit Grey Walter's machine, the electrical tortoise he called *Machina speculatrix* [2]. This was a device equipped with photoelectric cells, inducing a certain behaviour of the machine as a reaction to light. The tortoise avoided obstacles, guiding itself by light signals, and was capable of returning to a base point in order to have its storage cells recharged. Although somewhat similar to simple, instinct-governed beings, the automaton could not be called adaptive because it did not modify any of its internal connexions during its movements. Even less could it be termed a learning machine, since the machine neither recorded its experiences nor changed its behaviour in response to these (to do so, it would need a memory and a scheme of association of data).

Ross Ashby's homeostat [1, 3, 4], a random automaton, is an adaptive machine because external perturbations bring about, through interconnected electrical controls, changes in the system's pattern. Similar machines for the integral electrical modelling of physiological functions have been built in

Romania, as well [3, 4]. These models are adaptive, although not yet learning machines. (A player who changes strategy according to his recollection of failures or successes in previous games is, indeed, a learning machine.) Current system theory emphasizes the basic difference between (a) simple homeostatic systems, whose chief characteristic is maintenance of the system's structure and whose main concern is one of balance, and (b) complex systems, whose learning problems have other implications.

Complex systems, by which we enter the area of social, economic, cultural and other human organization, possess the following features. They are open not only towards the exterior but to the interior, too; and the interactions between their components result in changes in the very nature of the components. This is thus no longer mere self-regulation, self-orientation or adaptation to a changing environment; it is the case of a whole system continuously elaborating its own structure. The physical systems are predominantly of the equilibrium type; the physiological are homeostatic; and the ecological, social and structural are creative of new forms, or morphogenetic [5].

Some rules for learning

System theory points out the plasticity of the higher type systems, those in a constant process of action-reaction with their environment; the existence of a variety-generating mechanism (lending the systems an increased ability to represent or project in their own organization the variety of the environment), of a selection system for choosing the most suitable variations, and of an ability to preserve and propagate their proper and satisfactory representations.

A principal concern of system theory is to determine the specific rules of higher types of learning differing from ontogenetic and phylogenetic mechanisms, in which useful information is stored cortically or genetically. In contrast to these, society accumulates its basic experiences and representations of the milieu in an extrasomatic way through its cultural institutions and modalities. As the accent shifts from structure to process, the new school is less interested in balance and stability than in the capacity of producing variation, changing the structures, and in this way responding to changes in the environment.[1] This environment differs from the natural one which, with its slow reaction time, was regarded in the early days of cybernetics as a generator of perturbations that must be withstood; it is a highly changeable, plastic and influenceable milieu, in other words, a human and social one for the most part—a genuine partner that changes during interaction, and which thus becomes more of a transaction. Wiener contended, in fact, that

> To me logic and learning and all mental activity have always been incomprehensible as complete and closed pictures and have been understandable as a process by which man puts himself in rapport with his environment [6].

Researchers who deal with systems pay attention to the new element adduced by the learning process in complex systems, the new element being defined as a change in behaviour following the solution of a problem posed to the individual element by its relations with the environment.

There are several forms of learning

On a certain level, learning is but alteration of programme, sufficiently important to account for several types of learning: habituation, conditioning, successive trials, latent learning, intuition, and even intelligence (in which Piaget sees 'the highest form of mental adaptation'). This incorporation of objects in behavioural patterns, including

1. One model of the world, depicted by C. Hewitt, postulates a system of 'actors' who receive and send messages; in it, Hewitt describes their behaviour when faced with disturbances within the system.

accommodation and assimilation, is only a temporary reorganization of the parameters of the body's principal functions.

On a different plane, as we pass from the individual to society, there appears an additional resource for adaptation to the environment besides the reorganization of programmes: reorganization of the internal structure. Self-organization is thus added to self-stabilization. One of its current forms of manifestation is the progressive differentiation of subsystems and components.

At this point, there arises the need to assess a system's degree of organization in comparison with another's. The concept of entropy has been used for this purpose.[1] Some authors maintain that entropy can be applied to the economy in the classical meaning of the latter—production is an anti-entropic process, whereas consumption is entropic.[2] Others suggest that, in the case of economic and social processes, entropy should be used only as a means of measuring informational content. The internal organization of a system and the conservation, not of the structure but of the efficiency of the basic functions within 'ultrastability', are thus directly correlated with the learning processes.

The systemic behaviour of society is recognized in both the current language and the philosophy of history. Society is said to develop, grow or evolve. But when we say 'society learns', we use a concept embracing and explaining all the others, a concept indicative of the very mechanics of change.

Some scientific tools of learning

Let us now see how learning, in its various forms, has become a dominant concept in some salient branches of scientific investigation. One of the most viable directions of research stimulated by cybernetics is that of man-made intelligence. This analyses computational procedures and can imitate some of the advanced functions of man's nervous system and mind. The difficulties here are even greater than one would expect. A central theme of man-made intelligence is the representation of knowledge. But it is increasingly obvious that the axiomatic approach, by establishing fundamental rules from which the consequences can be inferred no longer suffices. In order to solve problems of this kind, a computer must receive specific knowledge, but this often exceeds its speed and memory capabilities.

There follows a chapter on pattern recognition, in which the information sciences join forces to solve a problem significant in several fields. A classic example is the recognition of typographic characters and mathematical symbols: scene analysis, object classification, weather forecasting and voice recognition fall into this group. Problems of system identification involve recognition of characteristics, e.g. automatic counting of the moon's or Mars' craters. But the most difficult problems are those of identification in a dynamic situation—when the characteristics of a process must be assessed so that certain performances are invariable. The learning algorithms, as they are called (because they 'learn' as the dynamics unfold), are now widely applied in biomedicine. Here they help to identify the human chromosomes, differentiate the white blood cells, classify diagnostic X-ray films by tumours and other anomalies, and so on. In industry, remote manipulators and robots have used the same basic learning methode that serve in the (artificial) control of prosthetic aids.

1. For a concise explanation of entropy, see Figure 1, 'Unterstanding the Laws of Thermodynamics', 'Can Thermodynamics Explain Biological Order?' (round table with I. Prigogine), *Impact of Science on Society*, Vol. XXIII, No. 3, July–September 1973, p. 160.—Ed.
2. See especially N. Georgescu-Roegen, *The Entropy Law and the Economic Process*, Cambridge, Mass., Harvard University Press, 1970, and, by the same author, *Bioeconomics*, Princeton, N.J., Princeton University Press (in press).—Ed.

What are the mathematical tools on which such research has relied? There are, first, the parametric algorithms of adaptation; these have reduced the uncertainties of a system by successive assessment of its parameters (although the same result can be achieved by taking as a standard the performance of a system). Pattern-recognition algorithms are said to be parametric or non-parametric. Recently, mathematical linguistics and the theory of fuzzy sets[1] have been added to the tool kit.

Information theory has made a significant contribution, too, by revealing the anti-entropic properties of learning systems. For the first time, it has been proved that a diminished entropy in learning occurs in the case of a non-physical system; this can be easily understood if we consider that ignorance is represented by an equal distribution of response alternatives, while knowledge and learning concentrate probability on fewer alternatives [7].

The picture would be incomplete without reference to the great effort being made by pedagogy to produce learning theories of an explanatory and practical value.[2] The largest classes of theory are those of stimulus-response association and Gestalt-field theory, related to cognitive field theory. The former category includes Pavlov's conditioned reflex, Thorndike's connexionism, Watson's behaviourism, and Skinner's operational conditioning; the latter includes the theories of Tolman, Lewin and Bruner. To these should be added the functionalist and psychodynamic theories, but we are still far from agreement and unification in the field [8].

Mathematics, transformation, language

Two books were published in 1957, which soon became classics, on the way in which man acquires the use of language—the chief characteristic to distinguish him from other animals. One of these, the work of B. F. Skinner [9], was an elaborate expression of the traditional theory of conditioned learning. The other, by Noam Chomsky [10], was to revolutionize psycholinguistics by advancing a new theory of language based on the assumed existence of inborn generative mechanisms which can be simulated by (a) models taken from mathematical logic and (b) suitable rules of transformation. During the twenty years of development of this new theory of language learning (which Chomsky has continuously improved), numerous psychological investigations have verified its hypotheses; and some of these have proved to be, at least in part, viable.

Other research efforts, many carried out in Romania, have confirmed a more general hypothesis according to which all types of human creativity repeat, in some sense, our linguistic creativeness. Hence, any process of human learning has, essentially, the architecture of the processes of learning and using language. This school conceives of language as the foundation of learning theory.

It is interesting to note that a general theory of human behaviour, in which both biological and linguistic comportment are included, is developed in the models of topological structure advanced by René Thom. There are various confirmations of this hypothesis, too, but I shall mention only three. There are the topological models of general learning processes as put forward by Japanese scientists [11], associated fundamentally with language structures. There is a general theory of human action initiated by Kotarbinsky which has led to models based on the theory of formal languages [12]. And, most elaborate, there are models for

1. Sets with unsharp boundaries, possessing different degrees of 'membership'.
2. It is significant that research in psychological learning for educational purposes is carried out in parallel, and even in the same building, with research on computers and learning automata. A vivid example is the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology.

the theory of form recognition based on grammars.

The development of biological forms can be simulated in two ways. There are discrete models, such as the various types of automata (from the rudimentary Fibonacci's strings to the complex pictorial grammars used in the theory of recognition of forms). There are also continuous models, such as those advanced by René Thom and based on the mathematical theory of catastrophes, i.e. models of a differential topological nature [13, 14, 15].

The most advanced probabilistic models of learning theory are those worked out recently by Bush, Estes and Mostseller, combining mathematical properties with physiological concepts. The mathematical tool used by these researchers is that of stochastic processes, or random processes possessing elements of probability.

The simple stimulus-response pattern, attacked by some as being mechanistic, has proved to be the best suited to assume mathematical forms and to be imitated by engineers. Thus, the mathematical theory of learning is built on experimental material relating to the pedagogical theory of conditioning. One of its most significant properties is that of reinforced learning, by which a system's or a body's response to stimuli is strengthened by a reward or weakened by a penalty. The favourable or unfavourable reaction of an environment to a response is precisely the path taken by engineers in constructing adaptive or learning machines.

Stimulus-response and a possible paradox

A theoretical paradox arises here. System theory, according to which learning is a characteristic of complex systems, is faced with the problem of the continuation (by both mathematics and technics) of the conclusions reached by the school of stimulus-response, which are in their turn inspired by simple systems. But this is a school which system theory rejects and contradicts in its very fundamentals. This is, then, a gauntlet to be picked up. As one observer has recently commented [16]: 'The psychology of learning poses the greatest problems to the student of general systems theory and its derived organismic principles.'

Despite criticism of the reflex school by system specialists, they have been obliged to note that mechanistic processes bring about some kind of learning, that machines exist, and that positive and negative reinforcement are facts of physiological life [17]. This underlines the need for new conceptual models of learning and for a renewed upsurge of learning methods in systems more complex than the biological and electromechanical, e.g. in problems of ecology, town-planning, environmental organization, and learning in society.[1]

I have cited examples of research in electronic engineering and psychology, where learning is a central goal. In defining the learning phenomenon, one distinguishes the following components: a system's interaction with its environment, changes occurring in a system as a result of this interaction, and the response indicated when change has occurred.

Confronted with other problems of contemporary science, the definition of the learning phenomenon helps us to recognize the phenomenon in a wide and unexpected range of interests. Genetics is working out the learning mechanism in our species, in order to put it to practical use. Immunity in medicine is another kind of learning process. Cell biology has been in transition from morphology to the learning properties of living matter. The essence of planning and forecasting lies in adaptation and learn-

1. 'The crucial theoretical problem here is the understanding of the process of human learning.... The problem of human learning is fundamental to the solution of all social problems.'—K. Boulding, *The Meaning of the Twentieth Century: the Great Transition*, New York, N.Y., Harper & Bros., 1964.

Learning about learning

The conditions for an interdisciplinary effort on the phenomenon of learning are met in Romania as follows.

There is the probabilistic school of Octav Onicescu and Gheorghe Mihoc who, in order to describe the phenomenon, have created 'chains' complete with connexions and applications. Specific work in the field has been undertaken by Marius Iosifescu, whose book on the learning processes is a basic text.

The valuable contributions of the informational school include a method for measuring a system's degree of organization and Silviu Guiasu's algorithms for recognition and prediction.

Research on learning in biocybernetic and technical systems can be credited to Mariana Belis, Constantin Balaceanu and Edmond Nicolau; in anthropology, to Stefan Milcu and Victor Sahleanu.

Linguistic studies applied to the genetic code and other forms of developing knowledge—studies developed by the school of Solomon Marcus—have won international recognition. There has emerged a remarkable school of operations research, to which Nicolae Teodorescu and George Ciucu have made outstanding contributions, while Ion Bucur has been dealing most competently with the theory of categories at the University of Bucharest.

Research in economic cybernetics, developed by the school of Manea Manescu, is about to result in a national and an international model; in these, the response to the environment and the mechanism of adaptation play significant roles. Breaking new ground in forecasting technology is Mihai Botez, while automatic systems are being intensively explored by Gheorghe Cartianu, Cornel Penescu, Aurel Avramescu and Mihai Draganescu.

Within the national educational system itself, there is great interest in comprehending the learning mechanism and deriving practical conclusions for its improvement.

ing. The new branches of mathematics, such as decision theory, are built on the same basic concept. The diffusion of cultural values is another kind of learning. Many phenomena in international affairs and in States' behaviour towards a changing environment can be reduced to learning. The acquisition of new concepts in the world order can be interpreted in the same terms. Even the marketing of a new product can be accomplished by using the laws of learning. An excursion through some of the current problems of science and society reveal, therefore, the marked topicality of the phenomenon of learning.

Three preliminary conclusions

From these considerations, we can briefly draw three conclusions:

1. While in the first cybernetic stage the unifying concept was that of information and communication, learning is now the dominant problem in many sciences; these by exploring the properties and behaviour of open, complex systems, are raising earlier interest in automatic regulation and control to a higher level. The variety of approaches to this problem in its different compartments—scientific, technological, or social—calls for an effort at unification,

at interdisciplinary co-operation (see box). The effects will be felt first in a technological field, that of enhancing the computer's ability to solve ever more complex problems; these involve not only recognition, identification and prediction, but also the planning of action, verification and justification.

2. As no single theory has been able to account for all forms of learning, we are witnessing a search for more comprehensive models. The two great, contending schools seem to be approaching one another: *associationism*, for which learning is a process of establishing new bonds (building parts into a whole); and *cognitive or field theories*, in which learning is considered to be the insight into relationships (the whole is primordial). In the current literature, one perceives many efforts to use the cognitive theories for engineering purposes (such as the creation of learning machines and pattern recognition devices), thus gaining the advantages which have seemed until now to favour the behaviourist approach. While the associationists have been successful in identifying the mechanisms of learning common to man, animals and simple machines, their aim now is to elaborate models explaining the learning process in man, society, and the more sophisticated automata.
3. All theories of learning have their practical effects. The theory of mental discipline, simply to train the mind, caused many generations of children to learn classical Greek and Latin. But today the pressure for more comprehensive theories of learning comes from a society searching for the best ways to adapt itself to a rapidly changing environment. Benefits are sure to accrue from man's augmented ability to solve global problems: energy, food, population, education, habitat, mastery of the oceans and space, and converting scientific discoveries into peaceful uses. How much time would thus be gained and how many resources spared? Seen from the angle of a new international order—making it imperative to enhance growth and close the existing technico-economic growth gap among nations (of which the educational and technological gaps are not the least)—better understanding and control of the learning process reveal all its practical and urgent significance.

And three main conclusions

We have seen that the systemic approach is providing some useful concepts in the elucidation of solutions which have to be tested on problems facing society. It is on this general note that I should like to conclude my essay, concentrating on three more or less specific points.

Let us take, first, the case of science and technology. In the language of this method, the technico-scientific revolution is creating a new environment for society, one characterized by change, by the appearance of new elements (which, to a mathematician, can mean a distribution of probabilities) with a strong social impact. These confront society, in turn, with new problems of learning and adaptation. In the same language, the subsystem of science should be an open one because closing the technico-scientific complex leads to dysfunctional social aberrations. A condition for social progress, as one author puts it, is 'the absence of cleavages, power centres and group interests in breaking and damaging the flow of information and feedback on the internal condition of the system'. A negative illustration is the arms race—the orientation of science towards destructive purposes and then covering this with a veil of secrecy. Arming for war is not only an absurd waste of resources; it is also a pathetic failure on the part of human societies to learn.[1]

Following this way of reasoning, a society preparing itself for the technico-scientific revolution must broaden the variety of its substructures capable of understanding or representing the variety occurring in the environment. These society must regard as a permanent store, maintained in several configurations in order to keep alive society's ability to detect, grasp and adapt new elements appearing in science and technology. This store is not only a receiver or transducer; it is part of the milieu, capable of anticipating solutions and generating discoveries.

Another imperative, readily expressed in system language, is to maintain the flexibility of research forms and their ability to combine into new structures according to the nature of problems, i.e. maintaining inter- and multidisciplinarity and the *ad hoc* forms of co-operation.

Still another valuable lesson is that of mass communication: broad dissemination, sharpening the awareness of society as a whole concerning scientific and technical reality, and involving society in a permanent, large-scale discussion of this reality's problems and its economic and social implications.

Two subsidiary findings

I refer now to the effort being made by the social system to keep itself, as a whole, in a learning condition through receptiveness to innovation and the cultivation of critical selection. Society's most important undertaking could thus be called 'learning to learn'. It is only in this way that society can employ the achievements of science in its major activities, to optimize organization and planning, to work out the best economic strategies, and to prepare decisions aimed at enhancing society's ability to move in an environment characterized by uncertainty. Society cannot produce more, even in stages, than it has learned to yield materially and culturally. Society and its level and rates of *development* are but the level and rates of *learning*.

Intensive research on the future has also made an impact on emerging theories of learning. These hypotheses are increasingly future-oriented in the sense that the answers to possible challenges are not readily drawn from an existing store; they are designed deliberately to meet these challenges. Emphasis is placed on imagining probable situations and the possible configurations of their elements. Learning from the past is thus complemented by 'learning from the future'. Hence the merit of *scenarios*, the relevance of models, and the restoration of creativity.

It is obvious that these approaches are well suited to our era of great complexity and rapid change, and they promise to be better conceptual tools than we had in the past, leading possibly to a more appropriate state of mind with which to cope with our problems. □

1. For a comprehensive treatment of the theme of science and war, see *Impact of Science on Society*, Vol. 25, No. 1/2, January–April 1976 (entire issue).—Ed.

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To delve more deeply

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Future meetings:
Unesco and the International Cell Research Organization are making the preparations for an international meeting on 'Information Processing in Sensing Systems', to be held in October 1977 in Leningrad (U.S.S.R.).

Unesco will be the principal organizer of the next decennial international conference on the brain, to be held in Paris in April 1978. The theme of next year's meeting will be 'Natural and Artificial Intelligence'.

The science of biometeorology

E. Stanton Maxey

Biometeorology is the study of (a) the relations between meteorological factors, physico-chemical systems and living organisms, and (b) the indirect effects—whether of an irregular, fluctuating or rhythmic nature—of the physical, chemical, and physico-chemical environments of the earth's atmosphere and of similar extraterrestrial space upon physico-chemical systems and (especially) living organisms.

The modern secular sciences have become increasingly abstruse through goal-orientation which has led them to discern more and more about less and less. These sciences seem to have increasingly alienated themselves from nature's holistic scheme and to have dissociated themselves from concern for mankind's place within this scheme.

In physics, the cost of discovery has become roughly inversely proportional to the size of new particles described. Witness the 360,000 litres of cleaning fluid sequestered 1,600 metres deep in an abandoned gold mine in the attempt by Raymond Davis to confirm the existence of the elusive solar neutrino.[1] The cost-per-discovery relationship in such a case limits some types of research to the major economic powers and, even there, the relationship tends to be self-limiting. (The hundreds of millions of Marks required to fund the Petra electron-synchrotron storage ring in the Federal Republic of Germany have not, as a consequence yet been appropriated.)

It has been said that an adversary will be gained if you reveal to someone his true nature, and this may be equally affirmed of the secular sciences. Their proponents often behave as egotistical *prime donne*, bound in their separate, singular performances. Emulating spoiled children, they strive persistently for centre-stage in the world's scientific theatre.

Physics and chemistry that pollute

That such sciences are all too frequently irresponsible spoilers of life is found

1. Present theory holds that 2 per cent of the energy from solar fusion is carried off by neutrinos. Chlorine bombarded by solar neutrinos was expected to produce radioactive argon. The argon was not found, implying the absence of solar neutrinos. The further concept of low-energy neutrino scattering subsequently provided an alternative hypothesis. It should be added that some astrophysicists contend that solar energy derives from electrical phenomena in space and that the sun is not a thermonuclear reactor at all. (cf. C. Bruce, in: S. Coroniti (ed.), *Problems of Atmospheric and Space Electricity* p. 577–86, Amsterdam, Elsevier, 1965; R. Juergans, 'Plasma in Interplanetary Space; Reconciling Celestial Mechanics and Velikovskian Catastrophism', *Velikovsky Reconsidered*, p. 137–54, New York, N.Y., Doubleday Co., 1976.

■ E. Stanton Maxey

The author—physician, aircraft pilot, biophysicist, inventor and mechanical designer—is a general surgeon actively engaged in professional practice and in work with acupuncture (since 1972). His studies of weather-related aircraft accidents have led to the hypothesis of 'pilot bio-entrainment', dealing with 'the adverse aerions, electric and magnetic fields' found within the microclimate of an aircraft's cockpit. Dr Maxey's address: Ocean Boulevard Medical Center, 921 East Ocean Boulevard, Stuart FL 33494 (United States of America).

in the atomic experiments of Hiroshima and Nagasaki, taken together with the subsequent nuclear proliferation among a number of nations seeking such weapons. A daunted mankind bows fearfully to physics. But who is its conducting maestro? Whose baton signals the rhythm of the performance of physics?

Chemistry, likewise, is not lacking in fault. As many urban residents know, chemical pollutants from factories intoxicate the air they breathe, and aircraft pilots often see industrial smoke dissipated over hundreds of kilometres. The lakes and streams in many regions of the world have lost their ecosystems. Chemical additives have adulterated the foods of all industrialized countries (and a growing number of developing nations). Synthetic herbicides, after aerial application to woodlands, can be found deposited in the fatty tissues of local species of animals and fish. Significant levels of these same herbicides are also detectable in the fatty tissues of humans afflicted with cancer. And life's most basic process, photosynthesis, is substantially suppressed by chemistry's DDT at the level of only 1 part per 100 million. Who, or what, orchestrates chemistry's score in the symphony necessitated by the survival needs of the planet? And to what cadence does the performance of chemistry march?

Few mature disciplines in science lack the self-centred predispositions I have portrayed for physics and chemistry. Yet a different and precocious infant has begun to emerge, almost unnoticed, from the ranks of science. This is the adolescent, sister-science of biometeorology—a robust young lady barely two decades old. Her debut on the world's scientific stage is accompanied by the definition you read in the introductory summary to this article.

The unique characteristic of biometeorology, as compared to its older, sister sciences, is that the discipline is integrative. The long, wearying and raucous roar of the parochial disciplines has fostered—through this new science—a fresh recognition that nature's symphonies are imperceptible through the singular voices of separate sciences. Biometeorology, having recognized the drum of Newtonian physics, the violins of the waves of de Broglie and Schumann,[1] and the reverberating harps of Mendel's genetics, orchestrates the symphonic concert. Encompassing as it does the voices of astronomy, the biological disciplines, chemistry, meteorology, physics (ranging from the celestial to the sub-atomic) and probably the psychic sciences as well, biometeorology is at once an integrative and wholistic orchestration. It harkens to the notes of nature's symbiotic voices and then strives to perceive the hand of a conducting maestro within the harmonies of known forces and newly recognized cyclical phenomena.

1. W. O. Schumann determined the theoretical frequency spectrum of the earth's resonant cavity system.

International Society of Biometeorology

An international society devoted to biometeorology was founded in 1956, with headquarters at Leiden (Netherlands); its membership of more than 600 scientists from fifty-one countries represents a variety of disciplinary backgrounds. The society, whose secretariat is supervised by Solco W. Tromp, is divided into eleven permanent study groups that concentrate on the following topical areas:

Effects of heat and cold on animals and man.

Effects of weather, climate on human health and disease.

Effects of weather and climate on animal disease.

Effects of weather and climate on plants and trees.

Ecological climatology.

Effects of weather, climate on crop protection from plant pathogens.

Biological effects of natural electric, magnetic and electromagnetic fields.

Physical, physiological and therapeutic effects of ionized air and electro-aerosols.

Architectural, urban and engineering biometeorology.

Physico-chemical and biological fluctuating phenomena.

Biological rhythms, with special reference to environmental influences.

The Society publishes the scholarly review, *International Journal of Biometeorology*. For additional information, see page 119.

The tapestry that is life

Life is the essential linking filament which, in biometeorology, is seen as the central thread woven by nature's systemic forces. The mingling of these forces manipulates —in remarkably complex patterns—the warp and woof, the colouring and even the sound of our bio-evolutionary tapestry. It follows that, in order to comprehend the weaving, we must acknowledge the existence of both weavers and thread. Our separate sciences serve this purpose.

Astronomy, having made striking advances during the times of the ancient Egyptian and Mayan cultures, is perhaps the most inspiring and certainly the most venerable of all scientific disciplines. We observe, in passing, that the cumulative mass of all our planets approximates only a thousandth part of the sun's, that the central mass of our solar system orbits about the heart of the Milky Way galaxy approximately once every 250 million years, and that the phenomena of the solar wind extend beyond Jupiter—probably to Neptune. It is noteworthy, furthermore, that sun-spots wax and wane in number in eleven-year cycles, traverse the solar equator over twenty-five-day periods and circumgyrate near the solar poles at periods approximating thirty-four days.

A biometeorological examination of astronomy impinges immediately on some of science's sacred taboos in that planetary configurations *vis-à-vis* biological phenomena make secure, to a disturbing degree, plausible foundations for a revised and improved form of astrology. Kepler devoted much effort towards developing a scientific basis for the 'music of the spheres' (1619). Sun-spot activity has been observed and, since 1700, recorded according to the Zürich relative sun-spot number (Rz). The Wolf number, defined in 1849, is an index which has been assigned to sun-spot activity retroactively to the year 1749. The approximately eleven-year cycle, superimposed on other, longer cycles, was refined to a period of 11.08 years: this is the resonance of the sidereal periods of the three inner planets (Mercury, Venus, earth).[1]

Coupling mechanisms are very complex phenomena; they include the known spin-orbit coupling of the sun and Mercury [1][2] and the possible spin-orbit coupling of Venus and the earth. John Nelson, a radio propagation specialist, studied records of disruptions of terrestrial radio communications dating from 1920 [2]; he noted striking temporal correlations of phenomena in regard to both the occurrence of sun-spots and the specific configurations of planets. (Sun-spots and their resulting radio disturbances depend on two or more planets being aligned unilaterally with, or at right angles to, or aligned on opposite sides of, the sun. Further calculation of lesser planetary influences came to allow the prediction of sun-spots and radio blackouts with 93 per cent accuracy, even several years in advance.) The pertinent factor is that the sun's activity seems to be intimately bound to (a) the cyclical, or repetitive, positioning of its planets as (b) our solar system spirals obliquely along its corkscrew-like path through the galaxy. Also of possible biological significance is (c) the fact that the magnetic polarity of sun-spots reverses itself about every twenty-two years.

The key forces of the sun

Especially germane is the fact that the earth's entire ecosystem is powered by the sun's physiology. Sunlight makes possible, as previously noted, photosynthesis, the prime force of all life. Emissions from the sun of charged particles impinge on the earth's ionosphere, provoking not only the auroras of our northern and southern polar regions but causing variations in the ionosphere itself and in the terrestrial electrical field as well. Magnetic forces stimulated by solar storms affect the earth's magnetic field, resulting in both communication blackouts and failures in the distribution of electrical power. Magnetic and electrical forces also affect all living systems, although by means of mechanisms less readily identified than those correlated with sunlight and rainfall.

To the degree that man, the most evolved species within the earth's ecosystem, is influenced by forces emanating from our sun, he may be said to be governed by the phenomena that control our solar orb. Inasmuch as planetary configurations regulate solar mechanisms, they obviously then influence our planet's ecosystem—and man himself within the biosphere. Thus we arrive at 'scientific astrology': man is governed by the planets.

Galileo invented the refracting telescope almost 400 years ago and astronomers have recorded sun-spots for almost three centuries, but biological witnesses (trees) have recorded such activity for periods longer by an order of magnitude. Historical records indicate that sun-spots were almost unobserved for the period 1645–1715; when auroral displays were again seen, in 1715, there was considerable puzzlement in Stockholm and Copenhagen. Later, Andrew Ellicott Douglass, who pioneered tree-ring dating (dendrochronology), noted the remarkable absence of the annular markings for exactly this period. Afterwards, he read a paper in the *Journal* of the British Astronomical Association and was thus able to correlate sun-spot phenomena with tree-ring evidence.

Since then, studies of tree-rings in the California redwood (*Sequoia sempervirens*, the oldest of which are about 3,500 years) and the Russian oak (*Quercus borealis*, as old as 5,000 years) have revealed that the earth has experienced recurrently severe

1. Resonance, as used by H. Sleeper and myself, means that the three inner planets are identically positioned in their orbits with respect to each other and the sun every 11.08 years.
2. Numbers in brackets correspond to references at the end of the article.

droughts approximately every 510 years. These arboreal analyses suggest that a drought of seven to fifteen years' duration will occur sometime during the period 1990–2020. Let us hope that astronomers, employing the immense capacity of modern computers, will be able to determine the planetary co-ordinates of a terrestrial dry period in order to forewarn—and thus forearm—an already dry world.

The biosphere as electrical conductor

Voluminous research has portrayed the weaving of the thread of life by forces within the dynamics of the earth's resonant cavity ecosystem. Franklin is credited with discovering that a wire attached to a high flying kite became electrified, although at least one Frenchman of the same period built a lightning rod which his servant observed to spark as a thundercloud passed overhead. Many subsequent studies have shown the earth's surface to be negatively charged with respect to the atmosphere (although the field's polarity may reverse briefly during the night). This field's orientation is known as a positive field gradient. The gradient at the terrestrial surface averages 120–150 volts per metre, but diminishes so precisely with increasing altitude that the sensing of the field at the wingtips, nose and tail of an aircraft can activate an automatic pilot and keep the aircraft level in flight.

At altitudes of 90–135 km, in the ionosphere's E-region or Kennelly-Heaviside layer, the air becomes heavily ionized and consequently highly conductive electrically. The Heaviside layer, whose ionized state persists day and night, reflects sound waves and low-frequency radio waves to the earth's surface. Thus the earth is seen to function as a solid sphere of negative charge within a conducting ionized shield of + charge, from which it is separated by a gaseous dielectric atmosphere. Schumann calculated the theoretical resonance of this spherical capacitor system [3] and, with the hypothetical assumption that the ionosphere is an ideal conductor, determined a basic frequency of 10.2 Hz (with upper modes of 17.5 and 25 Hz). Six years later, another specialist measured the existing natural frequency at 7.2 Hz [4]. The difference between the theoretical and measured values is attributed to the ionosphere being less than an ideal conductor.

We perceive, then, that we live within the dielectric space of a spherical capacitor system of cyclically varying field strengths and fluctuating electromagnetic frequencies. We begin to perceive nature's orchestration when we acknowledge that these variations and modulations are characteristic of the whole solar system rather than being an isolated property of earth. The electrical field gradient (and the magnetic field, also) exhibits diurnal, lunar, annual and eleven-year periodicities. Curiously, the maximal electric field—on the average, 150 V/m—occurs daily as the meridian of the north magnetic pole aligns itself with the sun.

But why should phenomena of the geo-solar electrical field concern us? The answer is that most, if not all, biological systems respond to such forces (e.g. the phenomena of electrotaxis, galvanotropism and plerositropism, the latter denoting the influence of constant electrical fields). In the case of plerositropism, plants grown in experimentally controlled positive gradients grow faster, germinate earlier and are more disease-resistant than similar controls grown in zero or negative gradients. One authority (H. S. Burr) showed, in 1939, that the electrical potentials of living trees mirror changing environmental potentials and that a dying tree exhibits abnormally low potentials before it appeared, to the human eye, to be diseased.

Some effects of field gradients

Quite independently, Semyon D. Kirlian, while photographing in 1949 objects under the influence of high electrical charges, stumbled upon the fact that among leaves of identical appearance those that were diseased produced deficient photographs. Kirlian and his wife had been engaged in this kind of research since 1939. The question of whether or not their photographic studies reveal the existence of a subtle energy matrix—sometimes called the aetheric or bioplasmic body—is being analysed in laboratories round the world.[1] In 1962, L. J. Ravitz found similar electrical field properties in human beings; he correlated behavioural perturbations among schizophrenic subjects with their individual, cyclical electromagnetic field phenomena [5].

A decade later, another researcher, S. Lang, showed that both rats and guinea pigs—once removed from an electrical field—retained water and developed electrolytic abnormalities resembling those observed among astronauts while in space-flight. The fact that these changes reverted to normal when a positive, 10 Hz electrical field was introduced leads us to suspect that the electrolytic abnormalities detected in the occupants of space capsules are not related solely to the absence of gravitational forces. In a similar study in 1965, yet another investigator found that his subject's reaction times were inversely proportional to the frequency of electrical fields (within 1–20 Hz) applied to the head. The field strengths he researched were in the range of the natural atmospheric field [6].

These findings compare favourably with work done in about 1940: findings that positive field gradient attenuated fatigue led to the installation in some bombers of the German *Luftwaffe* of 'antifatigue' devices. These generated electrical fields inside the cockpits, an application which today's aviation fraternity has ignored. Hospitals equipped with field-generating devices of this kind succeeded in reducing cross-infection among patients, and even stables so equipped became the scenes of less 'stall-walking' among horses. Indeed, an enormous body of scientific literature correlating biological with terrestrial electric field phenomena awaits exploration by interested students. Here the topic has been touched only to the scarcest degree.

Langevin ions, ultra-violet light and aerions

Upon inquiry into the geo-solar phenomena responsible for the terrestrial electrical field, we encounter an intricate intermix of subtle forces which lie beyond the scope of this article. One of the elements involved is known as the aerion. Aerions are single, or groups, of gaseous atoms of unbalanced electrical charge. If shy an electron, they are called positive aerions; if carrying a surplus electron, negative. And depending upon their mobility in an electrical field, we distinguish small, intermediate and large aerions. Langevin ions—large molecular clusters attached to Aitken nuclei which move sluggishly under the influence of electrical fields—are found in concentrations of 50,000/cm^3 in industrial, coal-burning regions; small aerions average only 500–1,500/cm^3.

The causes of aerionization are complex, but we can state with certainty that the decay of radio-active minerals accounts for some aerionization near the earth's surface and that ultra-violet light is highly ionizing within the upper atmosphere. The previously noted positive electric field gradient implies an excess of positive-*v.*-negative aerions overhead, but the mechanism whereby this charge is maintained remains quite unclear. The classical model, which credits thunderstorm activity with the charging process, remains unsatisfactory because many lightning bolts are of a polarity oppo-

1. A systematic analysis of Kirlian aura phenomena will be found in R. Guzik, 'Is the Kirlian Aura a Life Force or a Fact of Life?' *Impact of Science on Society*, Vol. XXIV, No. 4, October–December 1974, p. 359.

site to that which would be required. Aerion factors probably account, however, for the observed 20 per cent increase in the electric field intensity which accompanies the 100 per cent rise in the number of sun-spots during the solar cycles.

That aerions have biological significance is already beyond doubt, but research in this area is fraught with difficulty. One encounters not only aerions of opposite charge and varying mobility but also gaseous molecules of widely varying chemical nature. The attribution of resulting biological phenomena to (a) the electrical component, (b) the chemical action, or (c) a combination of the two has tested the mettle of many a researcher. Among the multitude of efforts in the field, one finds the early, large-scale studies initiated about 1919 by A. L. Tchyevsky in Moscow and the more recent work of A. P. Krueger in the United States and A. G. Sulman in Israel.

Nature occasionally provides winds unusually rich in positive aerions. Among these are the santana breeze of the western United States, the *Fohn* of alpine middle Europe and the *sharov* of Israel. These phenomena are associated with increased occurrences of migraines, asthmatic attacks, thrombophlebitis, heart attacks and exhaustion in humans. These anomalies can be made to respond favourably if patients are placed in microclimates in which the air is treated with negative aerions. Open wounds exposed to air rich in negative aerions have been observed to heal faster than usual. The breathing of such air through the mouth produces a reduced rate of respiration, elevated pH of the blood, diminished blood pressure, and increased resistance to surgical shock. These results await widespread medical application.

Skin resistance and the unconscious mind

Tchyevsky postulated two phenomena in order to explain the effects of aerions. The first is passage of electrical charges through the mouth, nose and lungs into the bloodstream; the second is the transfer of electrical charges from the air to the skin. The latter mechanism merits our further attention.

The current flowing through the human body under natural conditions has been estimated at $1.96 \cdot 10^{-9}$ to $5.4 \cdot 10^{-12}$ amperes; it depends on the voltage of the terrestrial electrical field, the degree of ionization of the air, and the resistance at the surface of the skin—all of which are variable. Phenomena of galvanic skin resistance have long been observed in physiological laboratories and put to practical use by law enforcement agencies in the form of lie detectors (whereby the emotional result of telling an untruth is reflected by an immediate change in the skin resistance of the person tested). These phenomena have been explored further in 'biofeedback' laboratories; bodily electrical activity is monitored electronically and suitably displayed so as to enable the subject to recognize and control functions normally governed by the (unconscious) autonomic nervous system.

It is thought that skin-resistance phenomena allow direct access to the unconscious mind [7] and this discovery, although being put to use by psychologists and psychiatrists, overlooks the fact that these same phenomena modulate one's acquisition of the earth's electrical currents. (Changes in resistance in an electrical circuit affect the flow of current.) Yet nature has engineered even more complex biological systems than this.

For 5,000 years oriental medicine has postulated that specific points on the skin's surface are related to specific internal organs. With today's electronic probes, no doubt remains of this. Acupuncture or *shiatsu* points exist on the epidermal surface, and their resistance averages only one-tenth that of the adjacent skin. We must infer, therefore, that environmental aerions exchange their electrical energy through the epidermis primarily at acupuncture points—rather than indiscreetly anywhere through the surface.

We can also suspect that positive aerions correspond to the *Yang* energy of Taoist medicine, and negative aerions to the *Yin*. These suppositions are greatly strengthened by modern electronic studies of acupuncture phenomena [8] and their computerized analyses. These reveal indisputable correlations between bodily and terrestrial electrical phenomena. The analyses require calibration to compensate for the seasons of the year because biological systems mirror so manifestly the seasonal electrical activity of the earth.

Physicians have great difficulty in accepting acupunctural phenomenology since there seems to be no physico-anatomical counterpart to the system of conduction, or the meridians, which Eastern medicine avers and which modern Western electrical studies have verified. Electrical impulses can be observed travelling along a meridian, but the conduction velocity is slow: about 10 cm/s. An electric potential delivered to an acupuncture point, furthermore, produces no steady current. Rather, the amperage follows a curve such as can be produced in the laboratory by the parallel coupling of a capacitor and a resistor, i.e. an immediate, high amperage which falls rapidly to a low, but level, plateau.

It is possible that these phenomena exist within a bioplasmic medium, such as certain Soviet researchers (V. Adamenko, V. Inyushin, G. Sergeyev) have proposed. We observe that electrical abnormalities in specific meridians correlate analytically with disease in related organs: e.g. a malady in the left lung is often accompanied by an electrically abnormal left-lung meridian.

Asian medicine contends that acupuncture systems underlie an even more subtle system of *chakra* energy[1] which influences the enzyme-producing endocrine organs, thus linking biological and terrestrial systems: *muladhara* (pineal), *swadisthana* (gonads), *manipura* (pancreas), *anahata* (thymus), *vishudda* (thyroid), *ajna* (pituitary) and *sahasrara* (pineal glands). Scientific support for this contention is still lacking, but there is evidence that enzyme systems accomplish nuclear reactions; a specific example is the fusion reaction of sprouting oats, wherein potassium is transmuted into calcium.[2] The enzymatic transmutation of atoms will be dealt with further on.

The nature of magnetic forces

If electrical forces are seen to manipulate the warp of life's tapestry, then magnetic forces seem to weave the woof. While charged particles are propelled along the axes of electric fields, they move at right angles to the axes of magnetic fields. Let us now examine the magnetic phenomena.

A gross approximation likens the earth's magnetic field to that which would be produced by a short bar-magnet situated at the sphere's centre, but the origin of the magnetic force itself remains unsettled. We can theorize on the existence of both large eddy currents and a heavy, nickel-iron core within the earth—the latter being supported by the discovery of nickel-iron meteorites which may have originated within the cores of other planets.

The intensity of our planet's magnetic field averages, in the United States, 60,000 nT, varying from 20,000 to 70,000 nT at different geographic points.[3] The magnetic field fluctuates continuously. The diurnal

1. Readers desirous of knowing more about *chakra* should consult R. Melzack, 'How Acupuncture Can Block Pain', *Impact of Science on Society*, Vol. XXIII, No. 1, 1973.—Ed.
2. The biological transformation of potassium to calcium by oat seedlings, as claimed by L. Kervran and J. Zündel, is being investigated by Drs T. Murphy and J. Jungerman of the University of California, Davis.
3. The nanotesla (nT) is the basic, rationalized unit of magnetic induction. It equals the gamma (unit of magnetic flux density), the weber/m^2 (the rationalized unit of magnetic pole strength), or 10^{-4} gauss (practical unit of magnetic induction).

modulation of about 50 nT probably relates to atmospheric electric currents primarily solar in origin, but annual lunar periodicities of about 2 nT and eleven-year periodicities are known. The magnitude of daily variations follows, quite clearly, the frequency of sun-spots. Solar magnetic storms may impose variations of 600 nT within a few hours, and terrestrial frontal storm systems often produce low-frequency (3–20 Hz) magnetic disturbances of 40–80 nT intensity. Low-frequency magnetic waves such as these efficiently penetrate even buildings containing steel and travel long distances without appreciable attenuation.

Some effects of polar orientation

Numerous magnetotrophic biological phenomena reveal the importance of magnetic fields. Evergreen seeds sown with the root sprout tips oriented southwards sprout four or five days sooner than those of other orientations; this is especially so if the seeds are sown at the half-moon. Even this effect, however, is not simple for it depends on plant dissymmetry, i.e. whether the plant grows with right- or left-hand spiralling: seeds from the left-spiralling group do better when they are planted with the seeds' root sprout tips pointed to the south. Greater growth rates, increased enzymatic activity, a larger content of chlorophyll, and improved respiration accompany the greater harvest (13–53 per cent) when seeds are planted selectively in terms of the magnetic field.

Physiological studies have shown that radio-active phosphorous from the soil is absorbed more efficiently from the northern and southern sides of plants than from the eastern and western. The roots of such plants have been observed to arrange themselves predominantly in a north-south direction. We can perceive from these data that biometeorology's contribution to agriculture could assist in alleviating the world's food shortage.

Biological systems of higher order are also affected by magnetic fields. Termites orient their nests along a magnetic meridian. Dancing bees can convey accurately the directions of pollen and nectar sources if their hives are placed inside compensating Helmholtz coils (used to normalize the magnetic field in the space between the coils). Fish and birds appear to navigate by sensing magnetic fields, and cows have been reported to produce more milk if housed in stalls oriented northwards.[1]

The influence of fluctuating fields

Many biomagnetic phenomena have been observed in the human being. The heart's variable magnetic field lies between 10^{-5} and 10^{-6} amperes per metre (A/m) and that of the head at 10^{-7} A/m. The rhythm of mammalian hearts has been paced experimentally, using external rotating permanent magnets [9]. In separate studies, the rhythm of the brain was seen to follow both terrestrial electromagnetic wave forms [4] and weak, externally applied, magnetic fields of 30–1,000 nT [10]. The latter evoke intriguing speculation.

It is now understood that basic cerebral rhythms reflect a person's state of consciousness [7], but the degree to which fluctuating environmental magnetic fields influence awareness remains a pressing question. It is known that low-frequency magnetic waves are present in many meteorological frontal systems (as much as 600 nT) and that human reaction times are prolonged if their frequency lies between 1 Hz and 6 Hz [4]. Studies of weather-related aerial crashes indicate that the pilots often behaved as if they had been disoriented or, perhaps, somewhat entranced. Biometeorologists suspect that the brains of these

1. cf.. also R. Wehner, 'Polarized-light Navigation by Insects', *Scientific American*, Vol. 235, No. 1, July 1976: bees and ants find their way home by a complex system to detect polarization of the light of the sky. —Ed.

pilots were responding to the environmental magnetic waves which so freely penetrate metals, and that catastrophes of this kind will be lessened once appropriate magnetic conditioning is introduced on the flight deck. Magnetic sferics (disturbances) were recorded by Wolfgang Ludwig in 1974 aboard an aircraft at almost 4,000 m. He then developed a pocket magnetic wave generator which, at 9 Hz, obtained improvement in 87.5 per cent of subjects.[1] As these phenomena become more widely recognized, biometeorology will have made its contribution to aviation.

Psychic factors

Perhaps the most enigmatic of all human experiences involve psychic phenomena. For centuries, organized science has mercilessly ostracized those attempting to understand psychic events scientifically. This long feud is not yet concluded, even though parapsychology has become an official branch of (in the case of my country) the American Association for the Advancement of Science. Has biometeorology a contribution to offer here? Potentially, it has.

Recent studies in California confirmed that a subject inside a 'Faraday cage' could perceive what a second subject was seeing at distances ranging from a few metres to 4,000 km [11]. A hypothetical explanation of the phenomenon is that its information transfer is mediated by extremely low-frequency electromagnetic waves. We have already noted that such waves travel long distances without appreciable attenuation, penetrate even metal shielding with great efficiency, and exist in the frequency range of what is known as the earth's Schumann resonant cavity system [3].

Other studies concerning psychokinesis —phenomena in which a gifted subject causes an object to move at a distance, without physical contact—indicate that the bioplasmic oscillations concentrated in a subject's brain become wave-coupled to the Schumann frequency during critical episodes when work is accomplished at a distance.

We thus infer that the function of incarnate man's psyche may, in fact, be somewhat mediated by the electromagnetically resonating terrestrial system. The latter's resonance period is the reflection of solar activity and, through solar activity, a reflection of the planetary configurations. We can speculate that solar winds, bearing charged particles which (like atomic explosions in the atmosphere) lower the Schumann frequency, may result in a terrestrial resonant frequency conducive to disease. We find tenuous support for this speculation in some brain research (notably by Adey, in 1974): the brain progressively 'spilled' calcium when weak fields of ultra-high frequency, modulated between 6 and 16 Hz, were applied.

Cyclical fluctuations and disease

The cyclical appearance of disease has been noted in numerous epidemiological studies. This includes an increase in heart attacks and cerebral strokes on magnetically disturbed days, the approximately eleven-year cycle in the incidence of infectious hepatitis, and the lunar periodicity of homicides [12]. Biometeorologists suspect the existence of an underlying mechanism in fluctuating magnetic phenomena. This suspicion is being strengthened as new data are accumulated, and nature's orchestration is becoming apparent.

One of the most startling bits of evidence derives from a study of the 'birth sky' —the planetary configurations—of parents and its correlation with that of their children. An analysis of 15,000 matchings collected from records in Paris [13] showed a correlation such that the probability of chance producing it was 500,000 to 1 against.

1. cf. W. Ludwig, 'Placeboeffekt von 10 Hz-Scheingeräten', *Z. f. Phys. Med., February* 1976, p. 83.

In similar analyses of Belgian, Dutch, German and Italian celebrities, it was noted that those successful in a given profession were born, for the most part, 'under' the same planets. Admittedly biometeorology offers only a crude beginning towards an understanding of these results but, as we have already seen, subtle mechanisms are now apparent whereby the configurations of planets can affect man's psychological equilibrium. Surely future epistemology will clarify further the grand orchestration of our existence and the various rhythms functioning within nature's forces.

Largely unknown to chemists is the research of Giorgio Piccardi [14, 15] who, for twenty-five years, has studied the speed at which oxychloral bismuth precipitates. He has noted short-term variations in the speed coinciding with solar eruptions, and annual and eleven-year cycles of variation. The annual variations are particularly interesting in that they suggest that this chemical colloidal reaction is influenced by the spiralling motion of our planet within the galaxy and its movement towards the constellation Hercules.

The settling speed of erythrocytes, or red blood corpuscles, was observed for twenty years by Solco W. Tromp. The curves plotting these speeds match temporally those produced in the Piccardi tests. These rates of precipitation and settlement have arrested the attention of biometeorologists specializing in physico-chemical and biological fluctuating phenomena; they imply that the functional nature of the water molecule is influenced by celestial relationships. How grandiose, indeed, is the orchestration!

Even though reluctant to admit these fluctuating phenomena, biologists readily recognize that life systems ubiquitously are equipped with colloidal mechanisms. Struggling now for scientific recognition is the fact that life systems have the power, through their colloidal enzymes, to exchange protons within various atomic nuclei—thus transmuting elemental atoms. Physicists, especially, are alarmed by such reactions; they are reluctant to admit that microorganisms may already be accomplishing transmutations otherwise possible only with great difficulty and the immense power available in huge atom 'smashers'.

Weak energy and enzymatic reactions

Nevertheless, the quantitative elemental discrepancies of potassium, phosphorus, magnesium, calcium and sulphur—observed in conjunction with the life processes more than 100 years ago [16, 17],—is the subject of a major scientific confirmation made by Pierre Baranger of the École Polytechnique in Paris. His language is eloquent:

> I have been teaching chemistry ... for twenty years, and believe me, the laboratory which I direct is no den of false science. But I have never confused respect for science with the taboos imposed by intellectual conformism. For me, any meticulously performed experiment is a homage to science even if it shocks our ingrained habits. Von Herzeele's experiments were too few to be absolutely convincing. But their result inspired me to [check] them with all the precaution possible in a modern lab and to repeat them enough times so that they would be statistically irrefutable. That's what I have done [18].

C. Louis Kervran has described many such experiments, one of which was especially shocking. Hens deprived of calcium soon laid eggs possessing weak, leathery shells. Upon being fed purified mica (a silicate of aluminium and phosphorous), the chickens

> greedily attacked it, rolling their heads in it and tossing it into the air while gorging on it so fast that they nearly choked. The next day they laid eggs the hard shells of which weighed seven grams on the average.

Kervran then proposed the enzymatic reaction

$$^{39}_{19}\mathrm{K} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{40}_{20}\mathrm{Ca}$$

and has since observed extensively, by quantitative chemical methods, the same reaction in sprouting oat seeds. Confirmation was provided in 1976 by J. E. Zündel, using chemical and neutron absorption methods.[1]

Physicists will object immediately that a nuclear fusion reaction of the type lies quite beyond the realm of possibility: the energy yield would cook the fowl. It would also incinerate the hen-houses—an occurrence the chickens are obviously intelligent enough to avoid.

But let the physicists be reminded that mass-*v.*-energy problems in the case of spontaneous, radio-active decay led them to discover the neutrino. What is now to prevent biological systems, ever mysteriously tapping energy sources, from utilizing the neutrino more cleverly than the radio-active atoms of the physicists? Olivier Costa de Beauregard has examined Kervran's data and suggested that the currently recognized weak-energy phenomena can accommodate theoretically the enzymatic nuclear transformations proposed, but the neutrino is still required.

Charting the neutrino sea

We have already seen that astronomers employ cleaning fluid as a detector of neutrinos emanating in the solar system. Astronomers and physicists agree that a penetrating, ubiquitous neutrino sea pervades the universe. H. E. Dudley has postulated a basic flaw in the $E = mc^2$ mass-energy equation. He hypothesizes that the energy realized from 'nuclear' reactions really derives from the energy-rich, subquantic neutrino sea. He warns that the unwitting detonation of a nuclear device during a period of unusually dense neutrino flux could ignite our planet.

It is curious indeed that the neutrino sea possesses basically the same characteristics formerly attributed—since the earliest writers in Sanskrit—to the aether. (The concept was discarded only after the interferometer experiment by Michelson and Morley. Present knowledge suggests that their apparatus would not have detected the aether). The neutrino sea and the aether appear to be one and the same.

As mentioned in the case of the Davis cleaning fluid study, the detection of neutrinos is a pressing challenge for nuclear physics. While exploring possible systems of detection and being unaware of the work by Baranger and Kervran, Ruderfer independently proposed that neutrinos could 'produce sensible effects in living tissue' [19]. He was concerned with using biological systems to detect a cross-section of low-energy neutrino scattering, rather than employing neutrino energy to explain biological phenomena. Ruderfer's mathematical calculations lend support to Kervran's findings.

Many separate studies suggest that calcium, chlorine, copper, fluorine, hydrogen, iron, lithium, magnesium, manganese, nitrogen, oxygen, phosphorus, potassium, silicon, sodium and possibly mercury play interrelated roles in enzymatic nuclear transformations. These reactions entail predominantly the addition or extraction of hydrogen or oxygen nuclei to, or from, other elemental nuclei.

Especially intriguing to agricultural scientists is the suspected nuclear transmutation $O_{16} + C_{12} \longrightarrow 2N_{14}$. Such a biological nuclear reaction could explain nitrogen deposition by some plants, e.g. clover. In the reaction, we see that carbon and oxygen nuclei from inspired CO_2 are fused enzymatically into nitrogen—leaving oxygen atoms to be expired as gaseous O_2. It is certain that a chemical process enabling plants to fix atmospheric nitrogen remains undefined.[2]

1. See footnote 2, page 109.
2. For more on nitrogen fixation, cf. J. Marx, 'Nitrogen Fixation: Research Efforts Intensify', *Science*, Vol. 185, No. 4146; J. Postgate, 'Rhizobium as a Free-living Nitrogen Fixer', *Nature*, Vol. 256, 31 July 1975; and J. Beringer, 'Transferring Nitrogen Fixation Genes', *Nature*, Vol. 260, 18 March 1976.—Ed.

Hence, the hypothetical transmutational origin of plant nitrogen cannot be scientifically rejected, lacking as we do results from attempted confirmations.

Biometeorology and the scientist

The biometeorological aspect of enzymatic transmutation of elements was explored as early as 1940 (by R. Hauschke) by making quantitative chemical measurements of the potassium and phosphorus appearing in watercress germinated every fourteen days over a year's time. The content of these elements varied as much as 16 per cent, more or less, depending upon the lunar position (whether at new or full moon) at the commencement of germination. Hauschke's diagrams also depict an influence by the solar cycle. It seems that the same subtle forces inducing sun-spots and causing predictable radio blackouts may also set the cadence for variations in the oxychloral bismuth reaction measured by Piccardi, the settling speed of erythrocytes and the enzymatic transmutation of elemental atoms.

Of such is biometeorology. Just as a wheel's hub is borne by all its spokes, so life is sustained by all nature's forces. Science, as it elucidates the various factors governing macrocosmic phenomena in the solar system and microcosmic events at the subatomic level, illuminates as well the role all these forces play in weaving the miraculous web of life.

Just as the vision of a lovely maid stirs a man's heart, so does biometeorology quicken the pulse of those first glimpsing it. Some rank savants of sacrosanct 'scientific' dogma will rise, however, in towering and bellicose rhetoric to profane the revelations of the new discipline. Institutional professors, aligned in narrow disciplines, often simply ignore biometeorology. But true scientists are men and women of humbler creed.

The truth is not fickle. Can one doubt that biometeorology, already well served by earnest and gentle people, will continue to pierce nature's veil? □

Truth, industry, and the temple of nature

The scientist should be a man willing to listen to every suggestion, but determined to judge for himself. He should not be biased by appearances; have no favourite hypothesis; be of no school; in doctrine have no master. He should not be a respecter of persons but of things. Truth should be his primary object. If these qualities be added to industry, he may indeed hope to walk within the veil of the temple of nature.

Michael Faraday (1791–1867)

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Developing our water resources

Adriaan Volker

Only very recently developed as a refined scientific discipline, hydrology has to cope with a complexity of problems concerning the present and future management of a vital natural resource older than mankind itself—water.

Hydrology, as a highly technical science, came of age late—less than twenty years ago—with the increased need for water that became evident after the Second World War. There was also a growing realization on the part of hydraulic engineers that the very design of their work depended much on hydrological criteria.

It was logical, then, that projections or forecasts were made concerning future water needs. The principal motives for this activity were (a) the fear of a water crisis and (b) the fact that the planning, design, financing and execution of major hydraulic works could take ten to fifteen years or more. It was thus imperative to look ahead.

But to make projections, we need first to have available data concerning present and (if possible) past uses of water. We also need to know if water has been used efficiently, ascertaining this efficacy in terms of the cost of water in comparison with the costs of other production components and with the availability of water. This is an important point to which we shall return.

Projections are usually made separately for the various categories of use, whether the water is intended for drinking, industrial production, irrigation, or quality control of water itself. Also to be taken into consideration are the requirements of water for navigation, recreation, and nature conservation. The methods of use-projection include extrapolation, expected growth of the economy, availability of water and its fair sharing among users.

The plans and expectations of growth

The extrapolation of curves depicting the historical record of water use has been the traditional method, generally utilized until about 1960, especially in connexion with the consumption of drinking water. Since most growth curves have shown almost exponential increase during recent decades, extrapolation is a straightforward procedure and has also been applied to predicting energy (power) needs. The technique is especially suited to prediction over the mid-range, say five to ten years, because when applied to longer periods of time the exponential nature of the curves leads to fantastically high projections. The quantity of water required in such explosive growth

1. This article has been adapted from a talk, 'Trends in Water Resources Development', presented before the annual sessions of the Institution of Engineers, Colombo (Sri Lanka), in autumn 1976. It is reproduced here with the kind permission of the author.

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simply cannot be made available with current technology.

It seems more rational to base the estimation of future requirements on the planning and expectations of economic growth. One could object that in this way the difficulties of anticipation are merely shifted to another field, since economists are also faced with problems of prediction. But this approach opens possibilities of introducing factors absent in the extrapolation method, especially if the country concerned has a more or less planned economy.

One cannot assume that the use of water for domestic purposes will continue, *per capita*, to rise exponentially; there must be some sort of ceiling, otherwise a period of waste will occur. In the case of irrigation—usually the biggest consumer of water—there is an obvious ceiling dictated by the amount of available, irrigable land area. Indeed, the capacity of implementation of irrigation projects and their financing are important factors related to the growth in use of water.

Finally, especially in arid regions, one could base one's calculations on the total quantity of water available after development needs have been met, and thereafter determine what kind of distribution among the various economic sectors or national regions would be fair. Social and even political considerations will play an important role in the allocation of water. The supply of water has as high a priority here as in the other approaches but, from the outset, a maximum is fixed in terms of *per capita* use.

Latitude in prediction

After this exercise, estimates of future needs are compared with existing supplies of water and the resources at hand following national development. The assumption that within a few decades man will possess no better methods of water conservation, conveyance, quality control, and the like, than he has at present is very pessimistic. There is, therefore, a fair coefficient of safety in the confrontation of needs with resources.

Projections are made on a national basis and on a much larger geographical scale. The best known exercise of the type is the Indicative World Plan of the United Nations Food and Agriculture Organization (FAO). The plan includes proposals for meeting prospective demands through the year 1985, and its implications have been studied by the United Nations unit now designated the Economic and Social Commission for Asia and the Pacific (ESCAP). The plan includes the developing countries of the region, including the large ones (India, Indonesia, Pakistan, Thailand) but excludes the People's Republic of China.

The region's population in 1970 exceeded 1,000 million and was expected to grow to about 1,820 million by the end of the period examined: an annual average rate of 2.6 per cent. In order to meet the region's food requirements at an acceptable nutritional standard, it will be necessary to raise crop production from 722 million tonnes to 1,521 tonnes (rate: 3.7 per cent per annum). To produce this food, both the areas under irrigation and the yield per hectare must increase considerably.

The irrigated area of 64.1 million hectares (about 158 million acres) must thus be expanded to another 28.2 million ha (roughly 69 million acres), while the average yield will have to rise from 2,420 kg/ha to 4,790 kg/ha—clearly a twofold increase.[1] So the area available to meet food needs in the ESCAP region will decline further from its current low value of 0.28 ha *per capita* to 0.17 ha per person—a situation to prevail untill well into the next decade.

A similar study was carried out in relation to the Second Development Decade of the United Nations (1970–80). The entire field of the development of water resources was considered: drainage and irrigation, flood control and soil conservation, hydro-electric power, and household and industrial water supply. The investment foreseen by this study came to some U.S.$ 63,000 million.

Water runoff and real needs

Whatever the real costs will prove to be, from a purely technical point of view the required development of water resources during the next ten to twenty years is certainly feasible. There is still room for expansion. This is true for Asia, for Europe, and for the other continents. The barrier will remain an economic one, mainly financing.

To get an impression of the order of magnitude of the figures reflecting both resources and need on a global scale, we can compare the annual runoff of all the world's rivers with the yearly water needs of the planet's population. The mean runoff of all rivers represents a volume of about 40,000 km^3, or 40,000 million m^3—although the uncertainty in this figure is admittedly considerable.

The annual need of the world's population for water consists, as we know, of water for drinking and domestic uses, but this is a relatively small amount. Much more water is required to produce food and other commodities. In estimating the water use of the crops on the small part of a hectare now used to produce the food needed *per capita*, we should keep in mind that rainfall assures this supply in some parts of the world. Elsewhere, irrigation is essential. My estimate is 250 m^3 per person per year which, for a world population of 4,000 million, comes to a volume of 1,000 km^3. But this is only 2.5 per cent of the annual runoff of our rivers.[2]

This estimate should leave us very optimistic about the prospects for water management, but it should be clear that our reasoning is somewhat defective in that it disregards the uneven distribution of river flow—in both time and space—as well as the fact that not all fluvial water can be used. On the other hand, a certain portion of the abstracted (used) water returns to the water course, albeit in polluted form. In the Netherlands, a significant percentage of the water coming from the Rhine River has already been used upstream in the industrialized Ruhr area of the Federal Republic of Germany. At any rate, the total global stock of water—which can be neither increased nor decreased—could meet greatly expanded needs.

What kinds of tools in the kit?

Before examining the problems of contemporary water management as they appear in the national setting, it is useful to look for a moment at the scientific arsenal available to deal with the problem. I refer specifically to the tools proffered by modern hydrology and the methodology of water resource development.

Since hydrology emerged three centuries ago from a speculative discipline, it remained for long, nevertheless, one of measuring results but with little scientific analysis. By 1922, hydrology became recognized as a geophysical science when a section for hydro-

1. These figures are admittedly at variance with corresponding data presented at the World Food Conference held in 1974.
2. Some authorities such as Holy (1971) and Lvovich (1973) have arrived at higher figures, but they have assumed the currently low efficiencies of irrigation.

logy was established within the International Union of Geodesy and Geophysics. The section was later transformed into what is now the International Association of Scientific Hydrology. International co-operation in hydrological research was thus the result of initiative on the part of the free scientific community: geophysicists who found hydrology to be an interesting (but not very exciting) branch of physical geography, and engineers designing structures related to hydrological and hydraulic problems.

These specialists were the only ones who could devote some of their time to hydrology, and they had at their disposal those elements of mathematics and physics which they had mastered. But in specialized physics and mathematics there existed concepts and methods which, after some adaptation, held much promise for application in hydrology. The problem of lack of co-operation in this field was not simply a lack of communication, with the engineers and scientists unaware of the others' problems and possibilities. The natural systems of hydrology are much more complex than those considered in certain fields of mathematics, the applications of which sometimes have to be simplified. Many of the methods of mathematics and fluid mechanics had to await the arrival of the computing power of modern, large-capacity calculating devices.

The situation required extensive collaboration and experimentation—hence, manpower and funds. It was chiefly as a result of the threat of a water crisis that all these tools and methods became available round about 1960. Since then, we have been witnessing an explosive growth in hydrology, partly as a result of the application of rather advanced mathematics. Hydrology became a profession, soon splitting into specialities of its own.

The variability of supply

One of the great advances made in hydrology about seventeen years ago concerned synthetic or artificial stream-flow data. The discharge of rivers is quite variable, very low flows alternating with floods. It is this variability which makes a dependable water supply (whatever its purpose) impossible without special, costly provisions such as reservoirs, diversions, pumping stations and embankments. To assess the variability sufficient real data on river flow are needed covering periods of as much as a century or more, but these long-term data are seldom available. There are two ways of resolving the difficulty.

The first consists of exploiting rainfall data, at least if these should be available for a period longer than that represented by discharge records: since river flow is generated by rain, some relation must exist between the two. This relationship is extremely complicated, however, because of the great number of factors involved and the variety of conditions within a river's basin. The unit hydrograph (developed in 1934 but not applied until 1945) was a primitive precursor of the black-box or conceptual mathematical models that came to the fore around 1960. Much research is being done to refine these conceptual models, simulating in a 'lumped', simplified way the various physical processes of river basin subsystems.

An essential point is that the many parameters involved can usually be determined only by model calibration, i.e. comparison of computed discharges for given rains with actually recorded discharges. This means that, when applying these models, true records of fluvial flow are still required. For the calibration procedure, three to five years of stream-flow data are needed. A limitation is that, at least in principle, the models are applicable only to relatively small river basins. The branch of hydrology dealing with input-output models of this kind is called parametric or deterministic hydrology.

The second solution to the problem of generating synthetic discharge data consists of analysing historical record series. Whereas in classical statistics independency of records is assumed, hydrological daily and monthly flows are often related and time series reveal a certain consistency. The application of statistics to hydrological time series has led to the emergence of stochastic hydrology, one separated from all deterministic approach. The objective here is to develop synthetic records extending over 500 years or more in order to obtain a clear picture of possible variations in river discharge.

Synthetic data do not form historical records; they constitute, rather, a possible time series possessing the same statistical properties as a given historical series. To ascertain these properties, records representing fairly long periods (two to four decades, at least) must be available—already a disadvantage in many cases. An advantage, however, is that the methods of stochastic hydrology can be applied to river basins of any size and, in fact, to any hydrological quantity manifesting a time series.

Studying system behaviour

Simulation of systemic behaviour extending over prolonged periods, as developed in hydrology, has also become an important tool in the planning of the development of water resources. In combination with the use of a computer and a long-term series of hydrological data, the behaviour of a system can be studied using different assumptions about water requirements and different alternative solutions for problems concerning the storage, diversion and conveyance of water. Rational choice can be made between variants like a single, large reservoir as compared with a number of smaller ones, in-basin storage as compared to interbasin transfer, the use of surface water as opposed to that of ground water, and so on.

The functioning of the systems analysed can also be studied, e.g. the effects of different water policies with respect to distribution and allocation in terms of differing uses in different regions. Economic factors can be introduced when the benefits of water delivery can be weighed against costs. A recent innovation in such studies has been the introduction of parameters regarding water quality, the so-called quality models. The application of all these methods facilitates the rational approach to optimal solutions.

When one ponders these new methodologies, one cannot help wondering what kinds of information were available to engineers designing the important hydraulic works designed between 1850 and the First World War, construction of which occurred not only in Europe and America but in Egypt, Mesopotamia, India and South-East Asia. On analysing the technical notes of the time, one determines quickly that the few hydrological data available were checked and carefully compared with other information. This entailed much extrapolation, a flair for which was needed to estimate the variability of hydrological parameters and their extremes.

There were perhaps two contributing factors to the success of these designs: there was less specialization than now, and engineers spent more time in the field. Although there is no question of a return to 'the good old days', we should admit that the widening gap between the results of hydrological research and the application of these to practical purpose is attributable largely to the continuing division of the field into new sub-disciplines.

Resources development: problems and prospects

We have seen that, on the global scale, water is still plentiful but that the commodity is not always available at the right time and place, at the quality desired. One indication of the ill-balanced geographical distribution of river water is the computation of the volume of water available *per capita*, on average, in the different regions of the world (Table 1).

TABLE 1. Average annual runoff, *per capita*

Region (selected)	Population (million)	Runoff (km^3)	*Per capita* runoff (m^3)
Asia (including Japan, Philippines)	1,688	7,190	4,260
Sri Lanka	12.7	34	2,700
Africa (including Madagascar)	294	6,050	20,600
North and Central America	285	7,150	25,000
South America	154	8,080	52,500
New Zealand	2.7	300	110,000
Europe	606	2,540	4,200
Rhine basin	40	70	1,750
Netherlands	13	90	6,900
World total	3,800	40,000	10,500

The disparities are obviously great. The figure for Asia is less than half the world's average; within Asia, the distribution is very uneven in different countries as shown dramatically by the low figures for Sri Lanka. The rich regions, because of plentiful rain and low population figures, are Africa and South America. (The Amazon River alone supplies almost 20 per cent of the runoff of all the world's rivers.) New Zealand still has enormous reserves, while the figures for Europe are low because of its high concentration of population. It is in Europe that the water crisis is imminent. The big industries of Europe and Japan have not been. set up where water is in plentiful supply.

On a global basis, the quantity of water detained in reservoirs is small, the total effective capacity of all man-made reservoirs in the world being of the order of 2,300 km^3. This is only 6 per cent of the mean annual runoff of all rivers, estimated at some 40,000 km^3. This small percentage results from the fact that no important reservoirs have been built on the largest of the world's rivers, including the Amazon, Congo, Ganges, Mekong and Paraná. In zones characterized by extensive use of water for agriculture and industry, many reservoirs already exist on intermediate and small rivers. A further increase in artificial storage would surely meet great technical and financial difficulties.

Another obstacle to further water utilization is the pollution of surface waters, not only by industrial but agricultural activity.[1] Mention should be made in this connexion of the possibly harmful side-effects of irrigation on soils, for example salination and waterlogging. So water pollution is a serious problem; although the current rate of abstraction of river water for various purposes is, as I stated earlier, but a feeble percentage of total river flow, pollution renders a large proportion of this flow unfit for most uses.

A case of de-pollution

The difficulties posed by pollution are not, however, insurmountable. Favourable results have already been obtained in one of the worst cases of pollution (by organic, inorganic and even toxic substances) of an international water course whose problems are among the most difficult to solve. This is the Rhine River in Europe; it carries the waste products of one of the largest industrial districts in the world through a rather

1. For a technical discussion of this pollution and what to do about it, see E. DaSilva, A. Burgers, R. Olembo, 'Health and Wealth from Waste: an Economic Incentive for Developing Countries', *Impact of Science on Society*, Vol. 26, No. 4, October–December 1976. —Ed.

small river basin inhabited by 40 to 50 million people. Progress has been slow, but the Rhine's case shows—from a technical point of view—that (a) the abatement of pollution is possible, but (b) high costs are involved, making water of good quality expensive. The case of the Rhine has also shown that the principle of 'the polluter must pay' had to be abandoned and the expenses required to attenuate the pollution needed to be shared by all the riparian countries concerned.

The management of water and its use have other effects, too. The landscape and ecology as a whole change, in some cases for the worse. The complex of these repercussions, the environmental impact and its problems, have provoked considerable agitation everywhere. The establishment of the United Nations Environmental Programme in 1973 underlines the importance currently attached to the matter. Yet I might say here that mankind could never have expanded over the earth and attained a degree of comfort without changing the environment. (The oldest examples of this are to be found in the civilizations of Egypt, Mesopotamia, and the Indus Valley.) Indeed, a large part of my own country, the Netherlands, would not exist if man had not interfered. It can even be said that the environment in the Netherlands has a man-made infrastructure. Our predecessors seem to have possessed the skill to make good environments, but we know little about their failures.

After this somewhat philosophical diversion, let me now turn to a concrete question. What can be done, both short-term and long-range, to alleviate the problem of water shortage so prevalent in otherwise humid zones? There are several ways of approaching the problem.

Principal categories of solution

There are, first, the non-conventional sources of water supply: modification of the weather, the towing of icebergs, and the suppression of evaporation. Only desalination has been tried, on a moderate scale, but desalination for general use is prohibitive in cost.

Much water can be saved, secondly, and often inexpensively, by more efficient utilization of water. There is considerable opportunity in irrigated agriculture, for instance, to increase efficiency by reducing water waste. A recent investigation by British and French experts working with the Organization for Economic Co-operation and Development (OECD), concerning the use of water in steel mills, has shown that consumption in such plants could easily be reduced by a factor of ten. Users are often not aware, it should be added, that a water problem exists; they usually take no preventive measures, therefore, until suddenly they must pay dearly either for water itself or the disposal of its wastes. In Europe, it should also be noted—and regardless of the economic system—economic incentives in the form of levies, added charges or special tariffs apply in order to control, to a significant extent, the availability and the quality of water.

Thirdly, for the long term, the maldistribution of resources can be resolved in another, bolder way. We can either transport water over long distances to the customer or else bring his industry requiring much water (or much power), or causing special pollution problems, right to the areas where water and power are available at low cost.

Bringing water to the customer, fourthly, often implies interbasin transfer over long distances. That this is feasible can be seen in the Snowy Mountains scheme in Australia, the transport of water from northern to southern California, the proposed Transbasin Channel in Sri Lanka, and several smaller projects in Europe.

Schemes much larger in scale, still in the same category, remain in the early stages of conception. There is the North American Water and Power Alliance, intended to carry water from Alaska and British Columbia southward to California, Texas and neighbouring Mexico. Another bold design foresees the possible diversion of partial flow from the Siberian Ob and Yenisey rivers towards the Arctic Ocean. It has been suggested, in Europe, that Scandinavian water be transferred to middle Europe. And, by damming the Baltic Sea in the vicinity of Copenhagen, an enormous reservoir of fresh water could be created, joining the water supplies of northern Europe with the industrialized, densely populated regions farther to the south.

Finally, there are even some science fiction-like ideas, such as diverting water from the Congo River in order to irrigate the Saharan borderlands.

Theory becomes practice

Schemes of such scope could have profound influence on the environment and the ecology of large parts of the globe. They cannot be seriously considered unless reliable prediction can be made of their effects. The detailed planetary circulation models linking the land, sea and atmosphere (constituting the dynamics of hydrology required for such forecasting) are far beyond our present capabilities.

Establishing industry in places where cheap water and power can be had is not merely a prospect. It is a current, observable trend, one of its decisive factors having been the decline during the past decade of ocean transport rates for bulk cargo. Minerals, for example, can be shipped at low cost thousands of kilometres for processing, and then further still for ultimate disposal. An aluminium smelter at Bahrain on the Persian Gulf, processing ore sent 10,000 km from western Australia, expedites the converted metal as far as Sweden, a market more than 16,000 km from the ore's source. There are comparable sites in Iceland and New Zealand, comparably remote from either raw materials or commercial outlets.

That the potential of the world's largest rivers—the Amazon, Brahmaputra, Congo, Ganges, Irrawaddy, Mekong, Paraná, and the Siberian rivers—has not been used leads us to conclude that there remain many other possibilities for removing industry closer to water.

What we obviously need at the global level is a comprehensive strategy of development for both water resources and economy as a whole. There is no basic reason for conflict of interest between the industrialized nations where water is scarce and the lands possessing better supplies of water—each group being endowed with specific natural as well as human resources. The problems involved to distribute rationally the water-production process stretch far beyond those of simply optimizing the water's use. It is the factor 'water', in itself, which makes such a worldwide strategy imperative.

It is my sincere hope that the United Nations World Water Conference will pay special attention to this problem.[1] □

1. The United Nations World Water Conference will be held in Mar del Plata (Argentina) from 21 March to 1 April 1977.

To delve more deeply

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Disaster prevention and control in the earth sciences

John Tomblin

Among the critically useful applications of our basic knowledge of the sciences, especially physics, and our ability to exploit mathematics to the advantage of man wherever he lives on the planet, is that of disaster prediction. Here are described what we are currently capable of doing to mitigate seismic and volcanic cataclysms and how we should be able to improve our capacity to predict these natural catastrophes.

Introduction

A disaster can be defined as a situation involving the loss of life, injury to life, or destruction of property on a scale with which normal emergency services cannot cope. It therefore implies the occurrence of an unusual event which was not adequately predicted in time or place to allow measures to be taken for the protection of the threatened people or property. The two main types of event which belong to the earth sciences and which are capable of causing major disasters are earthquakes and volcanic eruptions. The purpose of the discussion which follows is to describe and critically review the present level of exposure of mankind to these hazards, and the means of protecting it from them.

The two different types of hazard pose considerably different problems with regard to both the geographical extent and the nature of the damage, as well as the premonitory signs and the duration of the phenomenon. It is simpler, therefore, to consider each type of hazard separately.

The scale of earthquake disasters

Since earthquakes are capable of causing destruction over much larger areas of the world's surface, and are more difficult to predict both in time and in place than volcanic eruptions, they result in larger losses. Details given by Montandon [1][1] show that the mean annual death rate from earthquakes between 1926–50 was about 14,000. According to Latter [2], this rate diminished for the period 1951–68 to about 3,750. When data through July 1976 are added, however, the annual average since 1951 increases to at least 10,000, whilst for the last 7.6 years, and assuming the loss of 100,000 lives in the Tangshan earthquake of 27 July 1976 (for which estimates of between 100,000 and 1 million have been quoted), the mean annual loss of life has been about 29,000.

The only general conclusion which can be drawn from these numbers is that the mean annual loss of lives through earthquakes remained reasonably static during the present century. But with the progressive concentration of world population in urban areas, and with the spectacular recent increase (in many cities) in the proportion of masonry and other earthquake-susceptible structures—especially high-rise

1. Numbers in brackets correspond to the references at the end of the article.

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buildings—there is a corresponding increase in the potential for losses of unprecedented size in a single earthquake.

Means of earthquake disaster prevention

The means of earthquake disaster prevention fall into two broad categories: first, those which we consider technically practicable and ensure a fair measure of success in most cases; second, those which at present are likely to be only rarely successful, or which mitigate only limited aspects of the disaster.

The first category involves the identification of regions subject to earthquake risk, the reinforcement of structures to resist an appropriate level of ground shaking, and the avoidance of certain local areas identified as the most exposed to earthquake damage. Seismology has already identified high-risk areas in broad terms, for example in the form of earthquake epicentre maps from about the year 1900 onwards–published by the International Seismological Centre in Edinburgh (United Kingdom); by the National Earthquake Information Center in Boulder (United States), and by many other national or regional authorities.

In addition to these maps which show the distribution of instrumentally recorded earthquakes, there exist for most regions catalogues of earthquake damage, extending over the period of historical documentation (over 2,000 years for Europe and China, about 300 years for Latin America, and 150 years for California). From these data, earthquake risk can be assessed in the climatological sense, in terms of recurrence intervals for events of different magnitude (energy at source) and distance, or for events causing different damage intensities at the point of reference. The recurrence figure will indicate the mean interval between similar, consecutive events, but will specifically not define actual intervals between such events. Magnitude values at a given distance, or intensity scale values, can be converted into approximate maximal ground accelerations for structural design purposes.

A relatively new type of instrument, the strong-motion accelerograph, is now being installed widely in order to measure the strong shaking close to the source of the largest earthquakes. Systematic, large differences in the frequency and amplitude of shaking are seen between local areas of bedrock and of thick alluvium, and observations to date provide a basis for predicting the characteristics of a given site once the local geology and the distribution of near earthquakes are known. The seismic response of the different parts of a large building can also be measured by accelerographs.

Application of existing technology

With regard to earthquake-resistant building construction, the technology is being actively developed (e.g. Page *et al.* [3]) and practised at least for tall buildings and important engineering structures in most countries with high seismic risk. The identification of high risk localities such as those subject to particularly strong shaking because of site geology, or subject to secondary effects such as liquefaction or tsunami, provides cogent arguments for the restriction of future land-use in some urban areas which, regrettably, government authorities are often reluctant to accept.

A final, and much neglected aspect of earthquake-resistant building design which was illustrated especially in the Guatemala earthquake of 4 February 1976, is the urgent need for the upgrading of the standard of construction of private dwelling houses [4]. At the Unesco Intergovernmental Conference in February 1976, it was noted that a communication gap exists between the élite of structural engineers working almost exclusively on large buildings, and small builders who in some parts of the world are using new materials (new to them, e.g. masonry and reinforced concrete) without proper knowledge of the appropriate techniques; or in other parts of the world where traditional building materials with no resistance to earthquake are being used (e.g. adobe), there is a need to introduce some form of cheap and readily available reinforcement. It was also recommended at the same conference that not only small builders, but also the population in general, should be educated in simple, earthquake-resistant building techniques for private dwelling houses. In Andean, Central American and certain eastern European countries, this is probably the most important single aspect of earthquake risk mitigation.

Accurate earthquake prediction

The second category of methods for earthquake disaster prevention should be regarded as possible but not yet widely practicable. The most important of these is the prediction of specific earthquakes. If accurate to within days or hours, this will allow the evacuation of the population; and if convincingly established as likely to happen weeks or months ahead, this would allow, to a modest degree, the strengthening of some smaller buildings. The main limitations of this method at present are the low prospects for accurate prediction and the fact that although, where prediction is successful, the primary goal of protection of human life may be achieved, the loss of property and hence the economic disaster ensuing, may not be significantly reduced. A very comprehensive review of the state-of-the-art in earthquake prediction has been published by Rikitake [5].

Within the same category may be included methods such as the proposed control of seismic energy release, for example by pumping water to great depths in active fault zones—thereby lubricating the fault and hopefully producing frequent small slips rather than the long-term accumulation of elastic strain energy to higher and more dangerous levels. The feasibility of such control has been shown by the creation of man-made earthquakes through fluid pressurization of deep wells, e.g. at Denver, Colorado [6], but the high cost of such an operation along a major fault zone, and the possibility of triggering an earthquake of larger magnitude than intended, detract from the practicability of this method.

The case for earthquake prediction

Although the first of the two categories described above, i.e. the universal application and continued refinement of improved building techniques, probably remains the best method for earthquake disaster prevention, there are strong arguments for increasing research efforts directed towards earthquake prediction. The arguments are three. First, as a means of protecting populations which live in highly vulnerable structures and which cannot be rehoused more safely in the early future; second, assuming a warning period of several months as a means of identifying the areas which are most immediately in need of reinforcement for existing buildings, or alternative accommodation; and third, assuming a final warning period of a few days, as a means of double security for the occupants of nationally earthquake-resistant, but possibly vulnerable (e.g. high-rise) buildings, in the event of a particularly severe earthquake.

The case in favour of intensifying efforts towards earthquake prediction is also supported by the spectacularly successful example of prediction of the Haicheng earthquake of 4 February 1975 in China [7], in which, after one false alarm, the time and place of occurrence were successfully refined to the extent that the population in the epicentral region were warned to evacuate their houses only five and a half hours before the main shock, whilst factory work was allowed to continue as normal, and did so without adverse consequences, only 50 km from the epicentre. This success represented the reward of what must be the most massive human effort that has yet been made in earthquake prediction, although the fallibility of such effort has, sadly, been illustrated in the Tangshan earthquake of 27 July 1976.

The key to the specific success in China in February 1975, and to the general problem of earthquake prediction, is the wider deployment and gradual refinement of existing techniques and the continued search for new methods and more reliable criteria. Descriptions in the world press of the first success in prediction, and uncertainties about the efficacy of present earthquake-resistant building codes, have given rise to popular hope and demand for the early achievement of accurate earthquake prediction. Usami [8], for example, writes that

> the special background of earthquakes and earthquake damage in Japan and memory of tragic damage [enlarge] the social demand for earthquake prediction. People know the status of Tokyo and are afraid counter measures will not be [taken] in time for the next event....

Bases of earthquake prediction and prospects

With regard to what has been called the 'physical basis' for earthquake prediction [9], it is clear that a variety of physical measurements can be used as predictors, and that the coincidence of these various lines of evidence and their interpretation through the supposedly irreversible mechanism of rock dilatancy, opens the door to a deterministic approach to earthquake prediction. This provides encouragement that, given favourable natural circumstances and adequate monitoring by several different methods, there are excellent prospects that, as in the Chinese earthquake of February 1975, similar predictions involving the successful evacuation of the population will be repeated.

In Japan, in an inquiry (using the Delphi method) carried out among geophysicists, Usami showed that the successful prediction of earthquakes which may occur in the following month was estimated as achievable by 1990, but that it was not clear whether precision to within twenty-four hours would ever be consistently achieved. In the United States, no prediction resulting in evacuation has yet been made, although Press [10] claims that ten 'California earthquakes were preceded by tilt changes in the vicinity of the epicenter' and that 'precursory changes in seismic velocity have been reported for about 10 earthquakes in California and New York'.

One of the particular problems of earthquake prediction in Western societies is that the public is more exacting than in other parts of the world in its demand for accurate information, and would be quicker to claim compensation for any inconvenience or economic loss following a false alarm. In China, by contrast, a significant section of the population is involved in making simple observations aimed at earthquake prediction, so that as Adams [7] concludes after a recent visit to China, this has resulted... in... an awareness among the people that this is their programme, and that any failures or false alarms are the responsibility of the people themselves, as well as of the scientific experts. Such an attitude is essential if people are going to accept the disruption to their lives that must follow any earthquake prediction.

Cost-benefit assessment in disaster prevention

There is little difficulty in justifying, in absolute terms, any serious attempt at earthquake hazard mitigation. It has to be recognized, however, that major earthquake disaster will strike a given community only rarely, and that human optimism is generally such that, even within a few years of a catastrophe, the possibility of the recurrence of a similar event—and the willingness to take precautions against it—are rapidly forgotten. The commitment of appropriate funds and effort not only to earthquake prediction, but also to earthquake engineering, building codes, land-use regulations and disaster preparedness, must be sustained for several decades if rapid progress towards the goal of earthquake disaster prevention is to be achieved.

In a recent review, Press [10] claimed that

scientists can question the policy of a government that spends billions in construction but is unable to support research that would safeguard its own investment. They can question the wisdom of budgeting less than a tenth of a percent of the total construction investment for research on possible hazards.

At the same time as making the above claims, it should be clarified that the present status of earthquake disaster mitigation is that, with appropriate funding over several decades, there is an excellent prospect of achieving the prediction of many major earthquakes, but not necessarily all, in the region of intensive study.

For the immediate future, it appears that each individual government will weigh the advantages of various levels of investment in earthquake disaster prevention, and will provide funding according, first, to its available means, and, secondly, to the demands of interested scientists. These demands, if presented and discussed before the population, may be echoed by public demand. In any representation to the government involved, it is clear that the scientists will be finally answerable for their performance. It is most important, for their own credibility in the long term, that they do not overstate their present ability.

Perhaps the most hopeful, although imponderable, aspect of earthquake prediction is that within the last ten years numerous completely new physical methods and models have been developed for earthquake prediction (e.g. seismic-wave velocity changes, radon emission and the dilatancy model). It is possible that the next decade may provide technological advances which will result in new and even more effective methods of monitoring and data processing. In this respect, the ability of seismology to achieve new breakthroughs in earthquake prediction will depend on the present goodwill of funding authorities and, if a prerequisite for financial support, the gambling instincts of the more optimistic seismologists.

The scale of volcanic disasters

The scale of volcanic disasters, in terms of area seriously affected and population killed, is considerably less than that of earthquakes. Latter [2], for example, quotes approximate world casualty figures of 0.5 million from volcanoes compared with 5 million from earthquakes for the period since A.D. 1000. From 1900 to 1976, the mean annual population losses amount to about 14,000 from earthquakes, and about 800 from volcanic eruption. Similarly, the largest single loss to date from volcanic eruption does not exceed 100,000 whilst for earthquakes the corresponding figure is 830,000 (Shansi province, China, in 1556).

The total number of potentially active volcanoes or volcanic centres in the world is estimated by Latter to be about 380. If the mean area around these centres that are subject to disaster is assumed to have a radius of 10 km, then the total area of the world's surface threatened seriously by volcanic eruption is about 120,000 km^2. This can be compared with earthquake belts close to land which, assuming a total length of 25,000 km and width of 100 km, amount to a total populated area subject to high earthquake risk of about 2.5 million km^2, or over twenty times the area exposed to high volcanic risk.

The conclusion from these data is that volcanic disasters in the world as a whole represent between one-tenth and one-twentieth of the scale of earthquake disasters, but that damage from volcanoes is equally as intensive within the relatively small areas which they affect. In those countries which are small enough for a significant proportion of the population to live around the flanks of a volcano, the scale of the national disaster may be equally as great as that inflicted in a larger country by a great earthquake.

Furthermore, the coincidence of volcanoes with certain of the zones of high seismicity means that volcanic hazard is usually additional to tectonic earthquake hazard. In particular the subduction zones, which include island arcs and certain continental margins such as Central America and the Andes, are the location not only of many of the world's largest earthquakes but also of the most violent type of volcano.

The means of volcanic disaster prevention

The main difference between volcanic and earthquake disasters is that the former are almost invariably preceded by obviously abnormal activity at or beneath the volcano. This activity may include frequent local earthquakes and increased steam emission for up to many months before the climax, and ash or lava emission in stronger explosions over a period of, usually, between a day to a month before the destructive cataclysm.

The problem of disaster prevention therefore becomes, first, one of identifying abnormal local earthquakes, gas emission, ground deformation, or temperature increase in time for the authorities and population to make detailed plans for evacuation; and second, one of identifying the rate of escalation and hence the probability of a destructive climax. A detailed description and examples of the application of the various monitoring methods are given in the handbook, *The Surveillance and Prediction of Volcanic Activity*, published by Unesco [11].

The duties of the volcanologist are (a) to establish from the sequence and types of deposits, both historic and prehistoric, the probability of different kinds of eruption and the areas likely to be affected. Work of this kind will take one or more years to complete and should be done prior to abnormal activity. After abnormal activity has begun, the volcanologist will (b) advise government authorities of every new development, as well as on the probability of the eruption becoming violent. The authorities need, preferably before the onset of any abnormal activity, to consider what level of risk they are prepared to run for the population in various model situations to be specified by the volcanologist.

From my own experiences, I conclude that it is best for the volcanologist to quote numerical risk estimates (acknowledging that these are crude) to the government authorities. The two critical figures are (a) the possibility of the eruption becoming destructive, and (b) the minimal period of time in which it may become destructive. For both of these figures, the volcanologist will be guided by his knowledge of the history of the particular volcano, by general reference to the descriptions of events leading to serious eruptions at similar volcanoes elsewhere in the world, and by the sequence and rate of change of activity of the volcano in question.

Continuous observation of a volcano during a state of abnormal activity should provide a progressive refinement of the date and nature of any eruptive climax, whilst the use of the largest possible number of monitoring methods will give the most reliable prediction.

Concretizing the action

With regard to specific figures, the authorities should estimate as carefully as possible for each volcano the maximal time in which a complete evacuation could be called of those zones designated by the volcanologists as dangerous in the event of a major eruption. During a crisis, the volcanologists should give regularly updated numerical estimates of the probability of the eruption becoming serious within the critical minimal time for evacuation. Concerning the appropriate date for the return of the population, the administration will be guided, in the same way as for evacuation, by the probability estimates given by the volcanologists.

A tentative flow diagram for planning against volcanic disaster is given in Figure 1, in which the suggested activities of government officials and the volcanologists are shown in the left and right columns respectively, whilst the sequence down the diagram is divided into pre-crisis, alert, evacuation and return phases. From my own experience, it is clear that there are numerous potentially dangerous volcanoes in populated areas which have not received the attention recommended in the pre-crisis phase. In these areas, the government authorities have not made adequate provisions for protecting the population from volcanic hazard.

General conclusions

The most reliable prospect for earthquake disaster prevention, probably for the next several decades, lies in the wider application and refinement of anti-seismic building techniques. These give the dual benefit of reducing both human and economic losses. At the same time, the ability to predict individual large earthquakes, and thereby to reduce further human losses, will progressively increase in proportion to the effort devoted towards this objective. However, until technological breakthroughs provide for more accurate predictions in time and place, the attempt to save additional lives by the evacuation of threatened areas or buildings will lead to numerous and costly false alarms.

The fixing of a threshold level for calling an evacuation will develop gradually, first, from public willingness to respond to such calls and, second, from the ability of a national economy to absorb the cost. This will apply equally to earthquake and to volcanic hazard. For the assessment of each new situation, earth scientists will be required to quantify the risk. They should specifically not be expected by the authorities to call the evacuation, since this involves the balancing of the risk against the social and economic consequences of evacuation—which earth scientists are not competent to assess.

With reference to these consequences, it should be emphasized that, whereas the present feasibility of giving early warning for volcanoes has already resulted in evacuations of close to 100,000 people for several weeks, future predictions of major earthquakes might involve comparable risks, including the secondary effects of fire and tsunami, to a major city of over 10 million inhabitants. The physical possibility as well as the cost of moving millions of people, except very locally (e.g. outdoors), and for a brief time (e.g. twenty-four hours), need to be carefully examined.

In all potential disaster areas, pre-crisis meetings between scientists and the administrative authorities are essential to develop a mutual understanding, first, of the problems of prediction and evacuation and, second, of the personalities of the individuals concerned—hence an insight into their ability to perform calmly under stress. For both

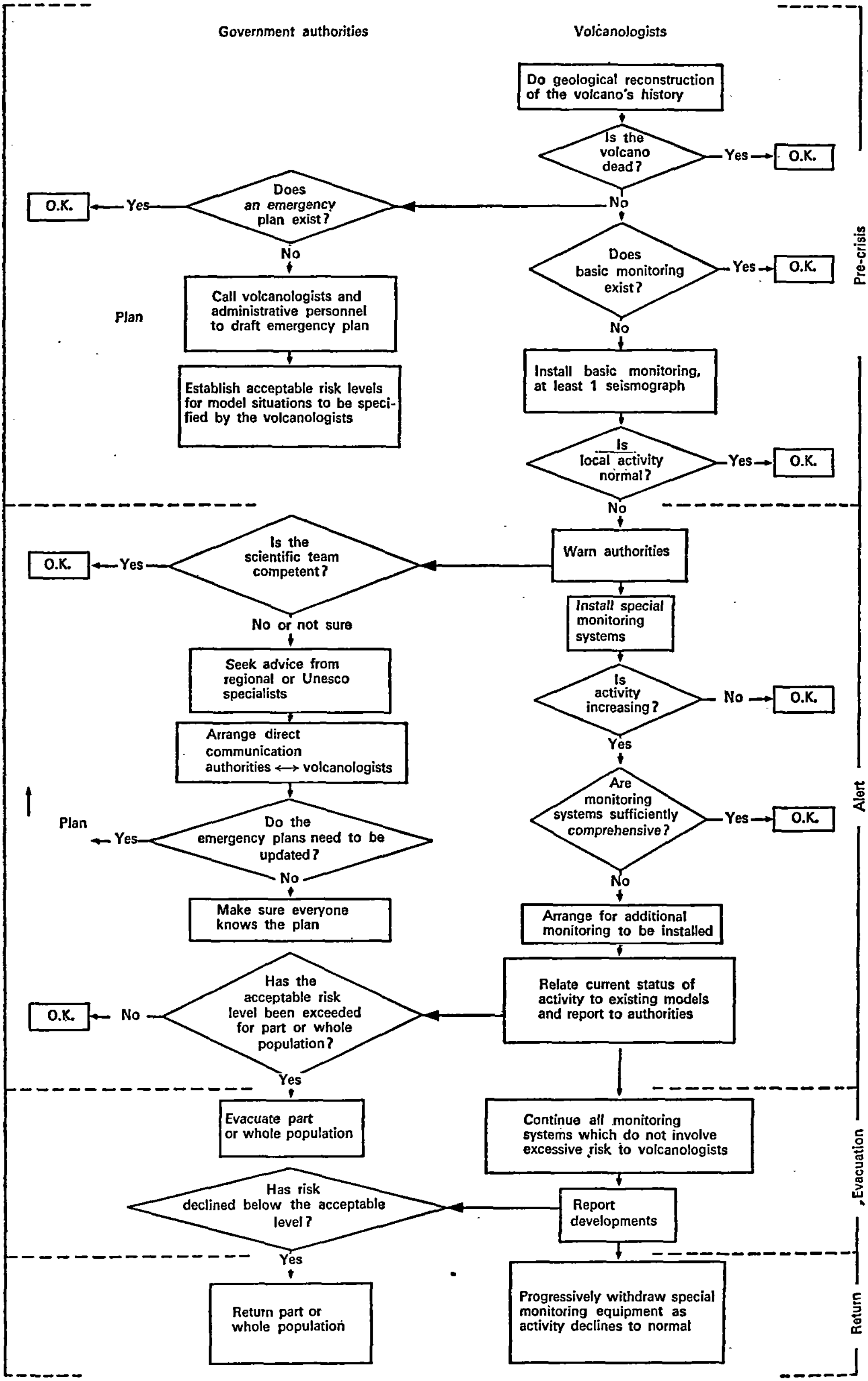

FIG. 1. Volcanic emergency planning: a flow diagram.

sides the making of basic policy decisions on the level of acceptable risk in advance of any crisis, will alleviate some of the uncertainties and anxieties which arise during a crisis. They may also halt what appears to be a world-wide tendency of increasing unwillingness, on the part of governments, to take any risk for the population in the face of abnormal volcanic or seismic phenomena.

Finally, advanced planning provides the important opportunity for scientists to be directly exposed to the public and the news media, and from this to learn the need to use simple language and to avoid the temptation of placing too strong an emphasis on the more spectacular and sensational aspects of earthquake or volcanic hazards. □

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To delve more deeply

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Letters

Human destructiveness: is science innocent?

Pietro Passerini, geologist, submits the following thoughts concerning the problems raised in **impact's** *issue on 'Science and War' (Vol. 26, No. 1/2). Our correspondent's address is: Istituto di Geologia dell'Università di Firenze, via Lamarmora 4, 50121 Firenze (Italy).*

The expectations of Sigmund Freud for a cultural evolution of society towards pacifism (p. 25 of your Vol. 26, No. 1/2) sound somewhat naïve, at least when one considers today's technico-scientific culture. It is still assumed that destructiveness arises only from the wrong or evil use of science and technology, whereas the proper, 'natural' destiny of knowledge would be to make man peaceable and wise.

I agree with the optimists that, from many points of view, knowledge may help reduce man's destructiveness. But the over-all effect of the growth and exploitation of knowledge is an increasingly thick network of individual, societal and ecological interactions which seem instead to foster mutual aggression.

Technological crowding

As was pointed out in the 'Science and War' issue, some uses of technology are avowedly destructive or have an obviously deleterious fall-out. The harmful pulsions incited by the technological environment are possibly less obvious, yet not less dangerous. An impressive instance occurs with the overload of interactions and constraints in motor traffic. A wealth of other examples is found throughout the urban-industrial habitat.

In an earlier letter to your journal (Vol. 25, No. 2, 1975), I suggested that, 'beyond a certain threshold, and in a society where individuals are more conditioned by social structures than by the physical environment, scientific and technical progress might reduce the scope of freedom instead of expanding it'. Peace needs adequate freedom. Technology has increased everyone's power, consequently everyone is continually injured by another's power (or else hindered by the constraints limiting the use of his own power). Hostility and violence are thus obvious outlets for such strain.

To be unable to *do* something does not directly rouse destructive behaviour. The lack of power can be overcome, in fact, but not destroyed. If one is forced or impeded, on the other hand, there is an immediate call for destructiveness: most impediments or constraints can, in principle, be destroyed. Here again science and technology, which reduce impossibilities while multiplying constraints, may be an intrinsic source of destructiveness.

There is a further complication: cultural crowding. As Erich Fromm pointed out in *The Anatomy of Human Destructiveness* (1975), cultural complexity broadens the field of psychical and social interests and attrition. The role of the growth of knowledge is immediately apparent in this effect, converging with the increase in technological constraints and interactions to produce conditions of crowding.

Organizational crowding

A possibly major destructive offspring of the development of knowledge is the tendency towards growth of large, strong organizations—the megamachines described by Lewis Mumford in *The Myth of the Machine* (1967) at the expense of small, weak ones. So knowledge in this sense is a tool for augmenting control through technical power.

But the world has come to be organizationally crowded, saturated by human institutions. In natural ecosystems, the tendency of populations towards exponential growth is checked by limiting factors. In the case of human systems, homeostatic systems seem to be far less effective in restraining the development of both mankind and its political, economic and bureaucratic structures.

Because of the pervasive growth of this organizational network, the world has become a closed (as well as overcrowded) system: anything new materializes only at the expense of the existing framework. Thus human organizations develop only by encroaching on the scope of each other, engendering a permanent state of conflict. Conflict could be considered as a kind of homeostatic control except that it fails to keep organizations trimmed to size. Result: the knowledge-organization cycle seems to be drifting, more and more, towards destructiveness.

Scientists are seldom aware of inconveniences in research. The latter are nicely screened by faith in the intrinsic value of scientific research, in the beneficial effects of 'progress', in the right to freedom of inquiry, and (last, but not least) by jealousy in preserving one's own social image. Researchers are often inclined, therefore, to reckon the negative consequences of their work in terms of the distortions attributable to those holding economic, political or military power.

Let's adjust the entropy

I do not consider the destructive effects of knowledge as something of an evil trick, a historical accident that could easily have been prevented if only our policy had been more sensible. Rather, I deem that destructiveness and conflict are partly the spontaneous consequences of the spread of scientific-technical knowledge. And, obviously, not all science is of the same sort; we cannot lump together the health sciences and nuclear energy. The harmless character of a specific branch should not conceal the effects of the development of all knowledge. We need to devise new strategies against a persistent, possibly intrinsic, trend propelling scientific-technical society along the road to disastrous results.

The issue of **impact** devoted to the theme of 'Science and War' solicited new ideas to help stop the warlike applications of scientific technology. Common sense would suggest that we limit any research that breeds great material power or creates large systems of interaction and that we encourage science meant to satisfy vital needs, to identify the very roots of violence, and to clarify the meaning of the development of knowledge in the evolution of man and his environment.

So we cannot reach the heart of the matter unless we consider anew knowledge's role in the genesis of human destructiveness. To oversimplify, we could say that scientific-technological knowledge represents (a) a tremendous accumulation of order and (b) a decrease in entropy in the sphere of man. What we call violence is often either the operation of this order or else a way to oppose it, and to recover our freedom we must adjust entropy to levels we can endure.

These must be among our basic tasks in the years to come, otherwise our destructive impulses will carry us beyond the point of collapse of mankind, this abnormal product of biological evolution.

Pietro Passerini

Results of readership survey

The reactions of our readers to the questionnaires enclosed with Vol. 26, No. 1 of the English and French editions of **impact** are given below. Replies continue to be received as of press time, so that the sampling below represents about 8 per cent of the paying subscribers to these two language editions. The italicized figures represent the French readership; all figures are percentages.

How long have you been reading **impact of science on society**?

Less than 2 years 23 / *21* Three to 5 years 45 / *33*

Six years or more 29 / *46* No reply *3*

Do you read **impact**

Regularly 69 / *68* Fairly frequently 28 / *23* Rarely 3 / *9*

On the average, how many articles do you read?

One or less 6 / *0* Two to three 35 / *32* Four or more 59 / *68*

Do you find the texts

Fairly easy 63 / *74* A little heavy 12 / *19* Very hard 3 / *2*

The right length 48 / *66* Too long 6 / *5* Too short 3 / *2*

(Because this question was sometimes answered twice, the percentages add to more than 100.)

The illustrations are

Too numerous — / *35* Adequate 74 / *42* No opinion 26 / *23*

The layout is

Modern 20 / *54* Acceptable 62 / *9* Lacklustre 8 / *37*

Old-fashioned 2 / *0* No opinion 8 / *0*

Your over-all impression of **impact** *is*

Serious, well-rounded 89 / *100* Too specialized 5 / *2*

Too light 2 / *0* No reply 4 / *0*

(The French readers' replies add to more than 100 because of multiple answers.)

Do you consult back issues?

Often 22 / *33* Occasionally 71 / *57* Never 7 / *9*

Do you make use of our articles in your work?

Regularly 14 / *9* From time to time 74 / *51* Never 12 / *40*

A few of the many, representative opinions which responded to the tenth and last question, '*What is there lacking in* **impact**?' follow.

. . . More emphasis on educational science and psychology. . . .

. . . More discussion on the problems of developing science in the Third World.

. . . Too few articles on the interaction between science/technology and political and social systems generally, and on the impact of [this] part of Western culture on other cultures.

. . . A little more *science* and a little less *society*!

. . . Too academic for the masses if it is for the Third World. . . .

An integration of philosophical elements and substantive issues [concerning] science and society. Most of your contributors have done one or the other, but not both.

. . . There is too uncritical [an] approach to authorship; volume is no substitute for quality. Incisiveness is lacking.

. . . Nothing is lacking.

. . . Continue discussing technical items.

Short notes about science today, science fiction, mathematical games.

. . . I am able to follow up trends in **impact** by further reading.

[More on the influence of] science in bringing forth the wholesome, creative individual....

What is the technology that science can produce for development?

Reports on activities of international science bodies and on Unesco's science programme....

[Your] authors are too exclusively members of Unesco.

... An issue on the sense and quality of living in all respects, not only in terms of ecology ..., but also on the ideologicalplane.

... More articles on technology (relative to education, manpower planning, economic prosperity), and less philosophizing about science.

What **impact** lacks is faith and an ideal....

Nothing [is missing]. It's fine, [but you need to be] promoted in industrial circles.

[More] on humour and the satirizing of science—even **impact**. Not enough technical detail....

It would be helpful to know coming topics.

Keep up the good work.

... Not very happy with one issue devoted to one subject. This destroys variety.

... You select the keynote of an issue and then search for articles to bolster it, not for those that disapprove or disagree. There aren't enough alternative views....

You do a good, solid job of presenting facts and opinions.

One or two less academic articles in each issue....

... Work on transmutation of the elements and on cosmobiology....

I preferred the lightness of the issues before the change in covers.

You have an excellent choice of subjects.

More exchanges of ideas concerning your articles....

Emphasis on the importance of women in all walks of life.

An issue on the centenary of the international convention on the metre.

Anything concerning the human body....

Town planning. The scourges of man and their causes....

Your subjects are well covered, very useful for General Studies [courses].

Some sense of the concrete....

Greater consistency....

Not enough articles dealing with the natural sciences..., and the protection of nature....

Diversity. . . .

A department reviewing key legislation governing science policy in the Member States. . . .

A statistical section, with R & D indicators by country.

In each issue, the views of a head of State concerning the subject dealt with.

. . . A glossary of the technical terms appearing in each article.

I would like to see more comprehensive bibliographies. You can omit the childish drawings, such as in the issue on 'Science and War'.

I liked the drawings in 'Science and War' and 'Appropriate Technology'.

. . . Needs . . . a much more glossy, trendy image. . . .

. . . More modern layout.

Too few relevant diagrams.

Sans-serif type is an abomination. . . .

Wider circulation.

Monthly appearance.

A regular, general bibliography. . . .

The possibility of contacting researchers concerning different subjects.

It is easy to say that you could do more in closing the gap between . . . science and society, which is your aim, but I can see no other way. . . .

The re-issue of certain exhausted issues.[1] □

1. In regard to the last point, we draw the reader's attention to the name and address of the reprint house appearing at the end of the editorial, page 5.—Ed.

In response to reader request . . .

. . . Your journal will publish regularly a list of editorial themes to be treated during the coming year.

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Vol. 27, No. 3 (July–September)	Science and Latin America
Vol. 27, No. 4 (October–December)	Modern engineering education
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Vol. XIV, No. 2, Summer 1976

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