R. Podolny

Something Called Nothing

Physical Vacuum: What Is It?

Mir Publishers Moscow

What does emptiness consist of? On the face of it, this question seems senseless. Emptiness is called emptiness precisely because it consists of nothing. But this is not exactly so. Absolute emptiness "exists" only theoretically. Real empty space, however, is not a simple void. It is a physical vacuum, a complex intermixture of spontaneously appearing and immediately vanishing fields. The deeper we penetrate into the region of ultrasmall scales, the more complex and rich in properties does this void — the vacuum — become.

If we descend farther and farther down, to distances represented by a decimal with 32 zeros following the decimal point (10^{-33} cm, a quantity difficult to even conceive), we shall find something entirely fantastic. Space resembles a sponge or a foamlike structure. It is a vacuum foam, undulating, continuously changing its shape and consisting of self-closing spatial bubbles.

All of this is vividly and fascinatingly dealt with in this book by the Soviet science writer Roman Podolny. Historical events and analogies, ' crazy" hypotheses and rigorous conclusions of theoreticians, interviews with well-known physicists, all this you will find in *Something Called Nothing.*

(From an article by a prominent Soviet physicist, Prof. V.S. Barashenkov, D.Sc. (Phys.-Math.), written for one of the Soviet youth dailies.)

Roman (accent on the second syllable) Podolny was born in Moscow in 1933. Educated as a historian, he has been engaged in science writing. For over twenty years he has headed a department in the Soviet magazine *Knowledge Is Power.* He has written twelve books on science and many articles. He also writes science fiction.

Something Called Nothing took part in a contest announced by the Znaniye Publishers in Moscow and was awarded a prize in 1982.

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Physical Vacuum: What Is It?

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Physical Vacuum: What Is It?

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На английском языке

Preface

You are about to begin a book on science for the general reader. It deals with the history of mankind's ideas on the Void, that great emptiness now called a physical vacuum. We know today that the properties of vacuum are much richer than those of any other kind of matter known to science. A wide diversity of fields, particles and much, much more exist in a vacuum. The more we find out about vacuum the more complex it seems to be.

The properties of the universe around us are governed to a substantial degree by the properties of vacuum. We can say that the laws of physics are "inscribed on vacuum". Quite another matter, however, is that we do not yet know for sure in what way these laws are imprinted there. Some things we do know for certain; others are still more or less guesswork. But it is already clear that all electrons are absolutely identical by virtue of the properties of vacuum, as are all protons and any other particles of each definite kind.

Science writing is frequently devoted to matters that are known with certainty and forever. The reader bowls along a paved highway that passes through country known down to the finest details. This book treats of a frontier of our knowledge and the poorly explored territory beyond it. We cannot be sure that the "reconnaissance data" that have been secured are faultless, or even that the front line has been accurately plotted. But, on the other hand, there is no need to denigrate the knowledge we already possess. Much on our map is correctly shown and shall remain there for all time. By no mere chance have certain advances in vacuum theory won their discoverers Nobel Prizes in recent years.

The present book relates the history of views, the development of ideas, often ones that are still in the making. It is, of course, more difficult to read such a book, but, in my opinion, much more interesting. The choice of these subjects is the more important because science writing is intended, in essence, primarily for young people. Hence, it can and should deal with the fields of science "where the action is"; informing the reader not only about what has already been achieved, but also about what still remains to be done.

I think this book has accomplished its purpose. I feel it should also prove interesting to professionals—scientists and engineers. In our day of narrow specialization, there is a great need for science books of a general nature that can broaden our outlook. Such books enable us to glance as if from a new point of view and in a new way at well-known matters. This, by the way, can be useful in solving highly specialized problems.

In excellent style the book relates the past, present and future of science. This historical approach is especially necessary when, as in this instance, we discuss a new branch of knowledge, where much is still unsettled. Even though we do know something today about what vacuum is and what its properties are, we are nowhere near any answers to questions on its actual structure and why, specifically, it has such a structure.

It is expected, as a rule, that a preface to such a book will discuss the scientific aspect of the subject, but in this case any attempt would be in vain: the range of disagreement between scientists on the problems of vacuum, as you will see, is quite wide. So wide that I, as the author of the preface, have no right to thrust my own opinion on the reader with respect to various specific scientific problems.

Any one who will read this book ten or fifteen years from now may already know (perhaps from textbooks) something about which scientist was right or wrong and by how much and how far.

I wish to add that the author undertook an extremely difficult task when he decided to write a book intelligible to the general reader on a field of science that lends itself very poorly to popularization, one reason being that physicists in this field employ the language of mathematics almost exclusively. The problems encountered in such a "translation" from the "mathematicalese" are innumerable. I contend with great pleasure that the author has coped with them very well.

M. E. Gertsenshtein, D.Sc. (Phys.-Math.)

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> Other mistakes may perchance ... await the penetrating glance of some critical reader, to whom the joy of discovery, and the intellectual superiority which he will thus discern, in himself, to the author of this little book, will, I hope, repay to some extent the time and trouble its perusal may have cost him!
>
> *Lewis CARROLL*

> FAUST (to MEPHISTOPHELES)...
> Let us fathom it, whatever may befall,
> In this, thy Nothing, may I find my All!
>
> *Johann Wolfgang von GOETHE*

To the Reader

Devotees of oceanography have long since claimed that our planet should be called the Water, rather than the Earth. They point out proposal on the fact that dry land occupies only twenty-two percent of the earth's surface. But if this principle is firmly applied, and developed in the light, so to speak, of available data on the structure of matter, we have every reason to call our whole universe the Vacuum. This is reasonable, not only because all the countless suns and planets are but tiny isles in the ocean of interstellar "near vacuum". Of no less importance is that in the stars and planets, in each of their atoms, the dense nucleus and its surrounding electrons are also surrounded by and immersed in vacuum.

This omnipresent medium called, as in ancient times, a vacuum, that is, emptiness, or "nothing", is by no means simply a container of all forms and varieties of matter. Vacuum influences everything it surrounds. But "influence" is too weak a word here. Scientists now know that what they observe in experiments in elementary particle physics is the result of interaction of the particles with one another and with the vacuum.

We know that the properties of elementary particles determine the characteristics of atoms; special features of atoms provide the blueprints for building molecules; and the structure and shape of atoms and molecules affect the properties of bodies in the macro- and mega-worlds, including the layout of our Galaxy and the Universe itself. But this Cosmic Whole, with its closely linked levels, is built, in one sense, on a foundation whose name is Vacuum.

Hence many laws that govern our world are dictated, in the final analysis, by what is called the symmetries of vacuum.

What's more, the elementary particles themselves are frequently thought to have been created out of vacuum. It may be that many puzzles of space and time have solutions concealed in the profound properties of vacuum. It may well be that space and time themselves can be called forms of existence of vacuum, if you take into account the true significance of the role that the physical vacuum plays in our world.

The history of the metagalaxy is, in fact, the history of the vacuum. There is hope that we shall find the key to many, very many problems of the past, present and future of the universe in what we still call by its Latin name: vacuum. I am sure that by now you like me are amazed by the commonly known translation of this Latin term: emptiness, i.e. nothing.

Up-to-date science, conducting research into the microscopic world and into space, into solid-state and elementary particle physics, and into nuclear physics and gravitation theory, finds it equally inevitable, though from different aspects, to take into consideration, and consequently investigate, the properties of vacuum as a special and extremely vital variety of matter. A radiophysicist and a nuclear specialist, a historian of science and an investigator of superconductivity all told the author and with the same conviction that one of the most fascinating and promising trends in modern physics is the study of vacuum. They maintained that this field may yield solutions to a great many problems of physics, and that advances in science will evidently be accompanied by a more and more profound understanding of what this great Something called Nothing actually is.

In the march of science, the phenomena being investigated are related by laws that are based either implicitly or explicitly on fundamental scientific concepts. From the very outset, emptiness was also included in these few most essential ideas of science. The Void preoccupied the keen mind of Aristotle, tormented Descartes, worried Galileo and bothered Newton. Conceptions of the void have changed down through the centuries together with our concepts of the world as a whole, but they always played a leading role in our picture of the universe, even during the times when emptiness was considered to be impossible.

> There are no useless discoveries! You must not tell a scientist to discontinue his research because it is unneeded today.... By scornfully discharging research that may now be abstract, but is actually levelled at unravelling the mysteries of nature and reproducing its phenomena, we run the risk of losing too much, because a knowledge of the unknown forces of nature is always followed by the mastery of these forces.
>
> *Mikhail LAVRENT'EV*

An apprehension of deep scientific problems plays an exceptionally vital role in understanding the world by man and in working out a true overall outlook. The idea of emptiness is one of these very general and deep concepts. It belongs, without doubt, to those general problems without whose solution a scientist would, according to Lenin, be doomed to stumble over particular problems. Look how often the concept of emptiness has served as the touchstone for a new physical hypothesis or theory! Modern approaches to vacuum are not only important and instructive for philosophers and physicists.

Its history, the history of emptiness, is also fascinating in itself and more generally, for it illustrates how man gains scientific knowledge. It can serve as a model for newer important solutions in physics and, moreover, in any field of science.

Here, with striking clarity, we see historical continuity and the onward march of science, and the kinship of investigators separated by centuries and millennia. We can see here the ties of time that support the unity of mankind.

You will not, of course, find in this book "the whole truth" about vacuum. And not just because the whole truth has not yet been uncovered. And not even because it would require a sizable library to set forth all the results available today, as well as all the profound theories and hypotheses that have been proposed before their time. Such a library would have to find room for many thousands of scientific papers that, in one way or another, touch upon the problem of vacuum.

"The whole truth" cannot be conveyed in this book primarily because vacuum is such an interesting subject, it is one of the most complex fields of science. It is also because in a book not addressed to physicists and mathematicians, it is necessary to tell about vacuum without formulas and equations, reducing to a minimum the number of terms and details in describing experiments. To really understand modern physics, you must use mathematics, the language with which, as Galileo discovered some centuries ago, nature communicates with man. Incidentally, I have only included two or three passages in this language, and they are quite comprehensible.

> Philosophy is written in this grand book—I mean the universe—which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering about in a dark labyrinth.
>
> *Galileo GALILEI*

Three hundred and some years ago, the Royal Society (more fully: The Royal Society of London for Improving Natural Knowledge), selected the Latin quotation "Nullius in Verba" as its motto; it means "Nothing in Words" or, more precisely, "Take no oath in words". This is the most concise statement ever made of the research principles of natural science.

Scientists must prove the truth of their views by their deeds, practice and experiments. A predominant role, and one that is becoming more overwhelming each decade, is played by mathematical calculations. These often appear as "thought experiments", "because all shades of meaning by a clever number are conveyed", as a poet once contended. In many up-to-date papers on physics, whether for the better or worse, words play the part, almost everywhere, of only punctuation marks, separating one system of equations from others, or of conjunctions that link equations together. (But, mark you, conclusions or a brief summary are always in words!)

In a story about science for the general reader, the motto of a storyteller is the direct opposite to that of the Royal Society and of all exact sciences. "Everything in Words" might well be the motto blazoned on the shield of one who resolves to write about science.

To a reader who opens this book with the hope of finding out everything on the subject, I can only advise: "Close it immediately!" Even what is already known by science cannot be described by words alone, still less what remains unknown. I have not presented exact proofs that certain phenomenon in nature is truly as described here. Nothing can be proved with words alone. Proof only comes from experimental results and calculations. There is no way in such a book to follow a most exact illustration of a most precise apparatus by a highly detailed description of the appropriate experiment, but only this would convince (or not) a specialist that all has been done properly. In exactly the same way, we cannot here merge brooks of mathematical formulas into the abundant rivers of scientifically stated theories. But all of this can be found in the books and articles addressed to those who know enough to find out more, to those who can translate by sight what is written in the universal language of nature.

What you have before you is neither a textbook nor a scientific monograph. I address myself to those who wish, not so much to clear up details, but to gain some understanding of basic principles: the course and laws of development of human thought as applied to the problem of emptiness, the ether and vacuum; the cardinal differences in the solution of this problem down through the ages; the conclusions of science based on experiments and calculations, and, finally, the human aspect in the acquisition of knowledge about physical reality. All of this, it seems to me, can be conveyed using only words. Moreover, only words will do.

> In science, more than in any other human institution, it is necessary to search out the past in order to understand the present and to control the future.
>
> *John Desmond BERNAL*

Does the Void Exist?

Physics is not only an exact science, but a historical one as well. And not only because of Karl Marx's statement that "we know only a single science, the science of history". It pays to always remember this appeal to perceive everything in the world in motion and development. No less important is that physics itself as a science retains a great many traces of its long trail through the centuries.

Even the familiar terminology of modern science is witness to its capability of being grateful to the distant past and reliably maintain the strong bonds of time. Astronauts (Greek for star navigators) are launched into space, or the cosmos (Greek for the universe), from the earth, their planet (Greek for wanderer). Vacuum (Latin for emptiness) is investigated by physicists (Greek for students of nature) by means of mathematics (Greek for learning by meditation).

Even sciences founded in the 20th century are given grand Hellenic names. Recall, for instance, cybernetics and biogeochemistry.

Long-perished ancient civilizations are still enriching our culture. Two great languages, ancient Greek and Latin, have not been forgotten.

Those who spoke and wrote in these languages frequently pondered over problems that still trouble us today. The conclusions they reached were, of course, on a greatly different level, but that could not be helped. It is always difficult to begin something new. But, like the biblical Adam, the ancient scientists gave names to so many things. And we dutifully repeat them: atom, poesy, history, geography, philosophy and a vast host of others.

The concept of the void was also put into use by the ancient Greeks. They called it *kenon*. This word did not take root in science. It was supplanted by the Latin word *vacuum*. Why? There were probably a great many reasons for this. It may well be that even such a matter, irrelevant on the face of it, as the sound of the word, played its role.

There are, of course, no direct, or even indirect, relations in the majority of cases between the meaning and sound of words. But still, we sometimes do find an interdependence between the definition of a word and its combination of sounds. This has been demonstrated experimentally: most people correctly guess which of two words they hear in a language unknown to them means "heavy" and which means "light".

The following is cited from a paper by L. A. Kitaev-Smyk, who has a post-graduate degree in medicine: "In ancient oriental language systems, the sound *u* or *ou* symbolizes emptiness, disappearance and negation. In pronouncing this sound, a person must imagine a cavity formed in his mouth with its bottom seeming to sink lower and lower. This is evidently called for to facilitate the 'disappearance' of some emotional disturbance, thereby tranquilizing the nervous system".

People who know the Russian language may have noticed that in the word *poostota* (emptiness) and the Latin word *vacuum,* the *u* sound plays no small part.

Did this happen by chance? I do not intend to follow in the steps of Romain Oira-Oira from the fairy tale for grownups called *Monday Begins on Saturday* by the science-fiction writers Arkady and Boris Strugatsky. Romain was engaged, in this book, in investigating the relation between the piercing properties of a glance (capable, according to the tale, of boring a hole through a concrete wall) and the philological characteristics of the word concrete. Worthy of mention, however, is that the Chinese word for emptiness is *kunshu,* and in Japanese it is *kuso* or *kuke*. On the other hand, there is no *u* sound in many other languages in the word for emptiness. Hence, the phonetic version for the change from kenon to vacuum is probably infeasible.

Maybe the reason is that the majority of the ancient

Greeks, as you shall soon see, denied the very existence of the void? It was hardly worthwhile, they thought, for science to retain a term meaning something that could not be.

Many things in this world had to be discovered by man. These include both the void and the air.

Air was, of course, discovered several centuries earlier. It was included among the basic materials that made up the world, being declared one of the four "elements" together with water, earth and fire. The ancient philosophers taught their disciples that everything in the world is made up of particles of one or several of these elements.

Somewhat later, a question arose in Greek philosophy: can one find a place where there is no earth, no water, no air and no fire; is a genuine void possible? To pose a question to the ancient Greeks meant that they would certainly make every attempt to answer it right off the bat, firmly and almost always categorically.

> Among the great things that are not within us, the existence of "nothing" is the greatest.
>
> *Leonardo da VINCI*

Leucippus and Democritus in their 5th century B. C. reached the ultimate conclusion: everything in this world consists of atoms and the emptiness between them. According to Democritus, to cut a piece of bread, sink a shovel into the soil, walk through the air and swim in a river are possible only because of the void between the atoms, themselves being indivisible. Hence, combinations of atoms forming the sea and clouds, stones and trees, and the bodies of animals and people are possible only thanks to the void. Only it can make way for motion, development and any changes in general. So, as we see, the void played no less role in Democritus' concept of the universe than a physical vacuum plays in ours.

The solution proposed by Democritus was both elegant and simple. Not in vain has this philosopher been revered for twenty-five centuries. In our 20th century, the scientists that founded quantum mechanics declared Democritus to be their forerunner as, at the turn of the century, did the forebears of atomic physics.

The following is a note made by Karl Marx in reading Aristotle's *Metaphysics*: "Leucippus and his associate Democritus say that the *full* and the empty are the elements, calling the one being and the other non-being—the *full* and *solid* * being being, and the empty non-being [whence they say being no more is than non-being, because the solid no more is than the empty]; and they make these the material causes of things."

Note that non-being, i.e. the void, is also recognized as being material. Emptiness served as well as an explanation why some substances are heavier and others lighter. Because, in the latter, it was contended, emptiness occupies more space.

Small ancient Greece was the home of a host of profound philosophers. Some discovered the existence of the void, whereas others spent their time proving that it was nonexistent. Among the latter was Empedocles, who proclaimed, "Nowhere in the world is there any void; and where would it come from?"

The doctrine of the impossibility of the void is a vital part of Empedocles' philosophy, which asserted the completeness and fullness of the world, and its development in conformity with natural laws.

As a matter of fact, he was not the first of the ancient combatants against the void. Emptiness is non-being they contended even before Empedocles (and after him!). Nonbeing, argued some of these philosophers, is not only nonexistent, but cannot even be conceived. In a word, there not only is no void, but to think of it is impossible.

Aristotle, the Prince of Sages, as he has been called for over two thousand years and "the master of those who know" as he came to be known in medieval universities, was of a different opinion. Different only in the sense that he held the void to be conceivable, but impossible to find in this world. On the one hand, contended this illustrious Greek philosopher, "...the investigations

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* Atoms.

of similar questions about the void, also, must be held to belong to the physicist, namely, whether it exists or not, and how it exists or what it is. . . ." On the other hand, there is no place in the world in which there is nothing; there is no such place and there cannot be. Why? Here he unleashed his infallible logic. If the void exists, then, in it, all bodies, heavy or light, stones and feathers, would fall to the earth with one and the same velocity; but this is, he concludes, impossible.

Strange, isn't it? The premise is true, but the conclusion drawn is false. And this happened with the very founder of the science of logic. Two thousand years were required plus the genius of Galileo to bring the premise and conclusion in line with each other.

In a void, Aristotle asserted in another argument, an infinite velocity would be possible, because motion would encounter no resistance. But, this eminent philosopher flatly maintains, an infinite velocity cannot, as a matter of principle, be attained.

Ergo, there is no void.

You are greatly mistaken, however, if you regard this to be naive reasoning. Scientific debates raged for twenty-three centuries about these matters. And, according to P. Kudryavtsev, author of an authoritative textbook called *The History of Physics*, it took Einstein to solve the problem posed by Aristotle. Einstein combined "the Aristotelian principle of the impossibility of infinite velocity with the existence of the void, taking as the limiting velocity that of light in vacuum".

It is now evident that physics is a historical science also in the sense that the solution of certain of its problems, and, frequently, not a final solution, may require whole eras. Today we seek answers to questions asked over two thousand years ago.

One of the outstanding scientists of our century, the biochemist Albert Szent-Györgyi von Nagyrapolt, was expressing not only his personal feelings when he wrote: "To me, science, in the first place, is a society of men, which knows no limits in time and space. I am living in such a community, in which Lavoisier and Newton are my daily companions; an Indian or Chinese scientist is closer to me than my own milkman. The basic moral rule of this society is simple: mutual respect, intellectual honesty and good will".

(The origin of science is a matter subject to dispute, and often to heated discussion. Some trace its lineage back to the Paleolithic period, i.e. the early Stone Age, whereas others are inclined to put its date of birth not sooner than the 19th century. These are obviously the extreme points of view. Most widespread are two opinions. The first holds science to be a creature of antiquity, the second, to be a product of the 17th century. I agree with the former of these. We shall not deal here with the finer points of methodology, but I am confident that everybody agrees that Euclid and Archimedes were genuine scientists.)

It remains to add that Democritus' argument (only the void provides the possibility of motion in space) was refuted by Aristotle, who contended that in motion bodies simply make way for one another. An example is a river in which new water flows in in place of the old water that has gone downstream. In essence, Aristotle here develops ideas that were proposed by Plato. In his famous dialogue "Timea" (famous, additionally, because it relates the story of Atlantis), Plato says that "since there is no void into which moving things can penetrate and our breath moves outward, it is clear to anybody that it is issued, not into a void, but pushes aside from its place what it is next to and this latter, in turn, drives away its neighbour. By virtue of such necessity all is carried away vortex-like to the same place from which it issued, enters and fills this space and again follows the breathing. And this takes place like a rotating wheel because there is no void anywhere". This is an account of the vortex theory, very popular in antiquity. It is an idea that was revived centuries later with new energy, as we shall see, by Descartes.

The strongest and, evidently, the most profound objection of Aristotle against the void, from the viewpoint of the 20th century science, is approximately the following. Throughout the void there would be no difference: no up, no down, no middle, no right, no left. Everything would be at absolute rest.... But this cannot be! In a void all directions have equal rights; it can in no way affect a body placed in it. What then determines the motion of the body?

In a space filled with some medium, according to Aristotle, the features of this medium serve as the cause of motion and determine its direction.

In a word, even the meager information given in the introductory chapter on the role of vacuum in the universe is sufficient to perceive the physical timeliness of the ideas advanced by this greatest of Greek philosophers.

The ancients could certainly ask questions and find answers to them. But checking the answers in antiquity was quite different from what it was and is in the science of newer times. The very investigation of the laws of nature under artificial conditions was thought to be impossible to the ancient philosophers. They usually drew a distinct boundary between what was created by nature and what was made by man, produced by his labour and handicraft.

Today, the modelling of natural processes is one of the most accepted methods of studying them. As to the ancient scientists (at least to the great majority of them), the idea of such modelling was inadmissible in principle; that which is natural was governed, in their opinion, by one set of laws, whereas all that is man-made complied with another set.

This does not imply that they conducted no experiments whatsoever (Aristotle, for example, carried out experiments on animals), but they drastically restricted the field of application of the results.

If mathematics was ever called upon to aid natural science, it was applied in ways that are almost naive from our point of view. The disciples of Pythagoras held that the magical significance of numbers is the key to all the mysteries of the universe. But this key, unfortunately, did not fit the keyhole.

"Let no one who is not a geometrician enter," is the inscription said to have been placed over the door of the Academy of Plato. But the most illustrious of the "graduates" of this Academy, Aristotle, rejected the very idea of applying mathematics in the sciences of nature. He declared that accuracy, namely mathematical accuracy, should not be required in all cases, but only for objects not concerned with matter. Hence, this method would not do for natural sciences, because nature, it can be affirmed, is always associated with matter.

It is strange for us, contemporaries of science that is inconceivable without "mathematical accuracy", to even hear of such statements. One might think that nature itself in Greece and the surrounding countries differed two and a half thousand years ago from what it is today, if their scientists considered it impossible to conduct investigations by either mathematical or experimental techniques.

What actually differed was not in nature, but in the society of the times. The science of that society, whether around the Mediterranean, in India or in China, excelled in its striving to learn the laws of nature primarily by reasoning, argument and logic. According to present concepts, this is negligibly little, and by far not enough to reliably establish even the simplest details about nature. It is the more amazing, then, that the ancients managed to achieve so much with such poor research principles.

A man's shortcomings, as they say, are extensions of his virtues. The virtues of antique science were, in some ways, extensions of its shortcomings. Scientific thought of that age was, in some respects, less fettered than any time subsequently. It strived to a greater degree to understand the world rather than to transform it. In this sense, the science of the ancient world was freer than that of modern times like a child is freer than a grown-up. Their scientists did not have to regretfully inform their colleagues: "Unfortunately, our calculations were not confirmed. . ." They almost never carried out calculations or conducted experiments. They were not very adept at calculations. When they did experiments, they considered, as a rule, that what happened in an experiment was one thing and, as has been mentioned before, what happens in nature is something quite different. Only in rare cases, before the last few centuries, could a scientist complain about the "great tragedy of science: slaying of a beautiful hypothesis by an ugly fact", as noted by Thomas Henry Huxley, the famous English biologist.

With such freedom, science provided staggering opportunities for what in art is customarily called self-expression. Hero of Alexandria, the great scientist and inventor who lived in the 2nd and 1st centuries B.C. and built the first "steam turbine", the first automatic slot machines for dispensing holy water in temples and many other remarkable mechanisms, followed Aristotle in saying that there is no void in nature. But, he added, it can be obtained artificially in a closed space. In the final analysis, again according to Aristotle: man-made objects obey laws differing from those obeyed by products of nature.

It should be pointed out, however, that he made one reservation. Hero's statements only concerned a continuous void. But a scattered void, one that separates tiniest particles from one another, Hero believed to be existing in reality, "like air exists between grains of sand on the seashore". Historians are of the opinion that this view of Hero was based primarily on the ideas of Strato, an ancient Greek philosopher who lived in the 3rd century B.C. and was a disciple of the disciples of Aristotle.

Diogenes Laertius, a historian of ancient philosophy, who lived at the end of the 2nd and beginning of the 3rd century A.D., compiled a long list of books written by Strato of Lampsacus. One book was called: "On the Void" About Strato himself, Laertius wrote that he was certainly a "praiseworthy man, excelling in all the sciences, and especially in physics, the most ancient and important of them all." This why he was given the name: Strato Physicus. Evidently, Strato was the particular philosopher that proposed two kinds of void when he tried to reconcile Aristotle's doctrine on the impossibility of a void with atomism, which required utter emptiness between the tiniest particles they called atoms.

Among the many advantages of the science of our time over that of ancient Greece is the possibility of correcting errors in much, much less time. Our scientific blunders may last years, even dozens of years, at worst, but not millennia. Progress, without any doubt!

There are two extreme attitudes that a researcher may have with respect to the world he investigates. Glorified in our time is the approach that Einstein described as follows: wonder is the mother of knowledge, and science is the flight from wonder. Aristotle, on the other hand, was of the opinion that an ignoramus is amazed that things are as they are; a wise man would be amazed if they were otherwise.

Einstein's words are closer to us, and not only because he lived in the same century we live in. The world astonishes us by its diversity, knowing more about it than was known ever before, we more profoundly realize the store of ignorance that is uncovered by each newly acquired item of knowledge. It remains for us to be amazed by Aristotle's statement, but we feel no need for flight from this amazement. This is so because we, belonging to the generation of the conquerors of space, can be envied for our confidence in the power, or even the omnipotence, of Reason. Socrates maintained that he knows only that he knows nothing. Aristotle, the disciple of Socrates' disciple, that he knows what he knows. The first of this opposing pair, Socrates, has become, in the words of Karl Marx, the personification of philosophy down through the centuries, and the second, Aristotle, is acknowledged to be the founder of a score of sciences. Including, by the way, physics whose personification in our time Einstein has become.

Let us then take flight from wonder and never forget that our knowledge is far from complete, but let us cherish our science, capable of explaining why things in nature are precisely as they are and not otherwise, and it is not by chance that "things are as they are".

And there is room in science even today, not only for human reason, but for human feelings as well. In the distant past, however, these feelings were vividly displayed, not only in the lives of the people seeking the truth, but in the very substance of their science, in its content.

In contrast to the discoveries of today's physicists, those of the ancient Greeks did not threaten the very existence of mankind. Nevertheless, their discoveries were apprehended with no less emotion than in our times.

The idea of emptiness, possible or impossible in nature, virtually haunted many scientists of ancient times and in the middle ages like a monstrous apparition. In the pages of school books, in science writing, and in essays on the history of science, we have all met the expression: "Nature abhors a vacuum", which came down from antiquity to the scholastic science of the middle ages. We found out that this fear was used to explain the principle of water pumps, which were used extensively in those times. Actually, up to a certain time, it was not nature that abhorred the vacuum, but the scientists who thought that they were following her example. But, in fact, they were just following Aristotle. Giving up the idea of the impossibility of a void proved to be more difficult, according to historical data, than to admit that the earth is not the centre of the universe.

Galileo Galilei, like Strato of Lampsacus and Hero of Alexandria, spoke of fine empty cavities in substances, but believed that they could only be of negligible size; nature would not tolerate larger ones.

Only the 17th century, the first century of new, experimental science, was able to discredit (though not entirely) the "terror of the void".

Evangelista Torricelli, inspired by Galileo, discovered experimentally, in 1643, that you can produce a void artificially. He thereby implemented a feasibility predicted long before him by Hero. All he needed was a dish of mercury and a long glass tube sealed at one end. After filling the tube with mercury Torricelli closed it with his thumb, inverted it and held it sealed end upward, immersing it into the dish of mercury in a vertical position. Then he removed his thumb and a part of the mercury poured out of the tube into the dish, leaving a column (above the level of the mercury in the dish) of about 760 mm in modern length units. Above the column in the sealed tube was a void, the emptiness that is still called a "Torricellian vacuum".

Some years later, in France, Blaise Pascal established the fact that the column remaining in the tube is lower on a mountain than on a plain, and that the column height varied with the weather. Pascal sarcastically asked the supporters of the "abhorrence of a vacuum" whether it is possible that nature abhors a vacuum less in the mountains than in a valley and fears it less in wet weather than when the sky is clear.

"...I became firmly convinced," wrote Blaise Pascal, "of the validity of the opinion I had always held, namely: that the void is not something impossible, that nature in no way avoid a vacuum with the abhorrence that some people think."

Worthy of mention here, by the way, is that the theoretical conflict with the void yielded appreciable results in engineering practice of the following decades. The invention of the barometer was only the first and by far not the most important of these. The next invention was the air pump, whose purpose was to obtain a "void", but it proved to be a milestone on the direct road to the steam engine, which, as we know, was one of the most important inventions making way for the Industrial Revolution.

The idea of the void began to occupy an important place in classical mechanics. According to Newton, all celestial bodies are immersed in an absolute vacuum. It is identical throughout, having no differences whatsoever. Newton, in fact, based his mechanics on the principle that did not allow Aristotle to accept the possibility of the void.

A Soviet philosopher, M. D. Akhundov, writes: "...in contrast to the void of Democritus, the vacuum of Newton is related to definite mathematically formulated dynamics and is laden with physical meaning through the motion laws, whereas its symmetry* is responsible for the fundamental conservation laws of mechanics."

Hence, emptiness, or the void, seems to have triumphed; it was demonstrated experimentally, and then laid into the foundation of the most influential physical and philosophical system in centuries. Nevertheless, the struggle against the very idea continued without abatement.

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* In the given case, its sameness.

In Place of Emptiness

The authority of Blaise Pascal and Isaac Newton was incontestable in the world of science. But opponents of the void, as had so often occurred previously, again turned up (further on, we shall see that Newton, himself, happened sometimes to be among them).

The chief argument advanced by those who were not castigated by Pascal's sarcasm was approximately the following: you say the vessel is empty, but how then can light and heat and magnetic force pass through it? But they do pass. Consequently, it is not empty, but is filled with some material medium....

Pascal was astonished and ironical in the same mood as before. "I grant you, dear Sir," we find in a letter he wrote, "the opportunity to judge for yourself: when you neither see nor in any other manner perceive anything in a given space, whose opinion is the more well-founded; one who contends that there is something there, even if he observes nothing, or one who is sure there is nothing there because he sees nothing there?"

All of these matters did not lead to a final solution of the problem of the void. "The King is dead. Long live the King!" they used to cry upon the death of a ruling monarch. Here everything turned out to be the other way round.

Emptiness was discovered. It could literally be seen in the long glass tube. But not everyone wished to be reconciled with this obvious fact; not everyone wished to recognize it. "Emptiness is impossible!" declared several eminent scientists, one after another. They included a man who could, among other matters, describe an experiment similar to that of Torricelli. And he could also predict the result that would be obtained. This theoretical scientist was the French mathematician René Descartes.

After predicting the discovery of emptiness, Descartes then declared that this was not a genuine void.

He wrote, "We consider a vessel to be empty when there is no water in it, but, actually, air remains in such a vessel. If we remove the air as well from the 'empty' vessel, again something should remain, but we simply do not perceive this 'something' ".

In the upper part of the Torricellian tube there was neither mercury nor air. But, according to Descartes, there was something else there. Sometimes he called this something "ether".

Everybody has heard the word "ether". But what unlike meanings it acquires in different situations!

Middle-aged and older people may still remember the smell of ether given to them as an anesthetic before a serious operation.

"An ethereal being," they used to write in old novels in praise of tender young ladies, though later this expression acquired a rather mocking tone.

When we turn on the radio set we usually ask, "What's on the air?" But in John B. Priestley's play *Dangerous Corner* Gordon Whitehouse, in a similar situation says somewhat ironically, "What's disturbing the ether tonight? Anybody know?"

"The concept of ether in modern physics has been replaced. . .," we are informed by a dictionary of philosophy.

What, in fact, is this "ether"?

I first mentioned the ether in connection with Descartes. Actually, this concept has a resplendent history that began somewhere in the dim past. We shall have to turn again to the Greek philosophers.

As a matter of fact, they were not the ones who thought up the word "ether". They took it ready-made from the rich stores of ancient Greek mythology.

The Genealogy of the Ether

Ether has a family tree that staggers the imagination or, more exactly, several such staggering family trees. In ancient Greek mythology, Aether (beginning with a capital "A") is the son of Erebus, darkness of the Underworld, and his own sister Nyx, the goddess of Night. Though a child of such gloomy parents, Aether ("the atmosphere") was a creature airy and volatile. He was simply the special air at the summit of Mount Olympus, the home of the gods, that is, the air breathed by Zeus and his relatives that lived there. Two dark forces, dark in the literal sense, gave birth to Aether, especially beneficial for divine respiration. This noble line did not, however, end on Aether. After wedlock with Hemera (the Day), Aether begot no less than the Earth (Gaia) and Sky (Uranus), the Sea and Oceanus, and even the infernal abyss Tartarus, below Hades, the Underworld of the ancient Greeks.

No clear-cut logic is evident in the aforesaid, especially if we recall that Aether was only air ("the atmosphere") at the summit of a terrestrial mountain. It is an idle pastime, however, to expect logic (in our sense of the word) in ancient myths. On the contrary, the downfall of the ancient myths is closely associated with the triumph of logical thinking in European culture.

A kind of explanation as to why the ether (or Aether) has such a family tree and such offspring can be found in the statement, known from later sources, made by Pythagoras of Samos. He contended that "the air near the Earth is stagnant and unwholesome, and all that is in this air is mortal, whereas the air on high is in perpetual motion, clean and healthy, everything in it is immortal and thereby divine".

Aristotle attached a strictly scientific meaning to the word "ether". He denied, as we know, the very possibility that emptiness exists. What should occupy a place where there is no earth, no water, no fire and no air? It became necessary to introduce the fifth element into the universe, the fifth essence, the fifth substance, that became much later to be called by the Latin word "quintessence". The ether, taught Aristotle and his followers, is not simply the fifth element, enjoying equal rights with the other four. It, they said, was the progenitor, the essence of all things, the basis underlying all the other elements of nature. Aristotle called ether immortal and divine, and deciphered its name as a compound word meaning "eternally in flight". According to other sources, ether is a Greek word meaning "blazing" and was given to the substance of which the ancients thought all the heavenly bodies, notable for their emitted light, were made.

The actual application of the word "ether" in this meaning was quite justified if you recall the ties of relationship of the mythological Aether. He, as you recall, begat the Earth and Heaven and the Sea, not to mention his other offspring.

There was, however, no agreement among the ancient Greek philosophers as to what ether actually was (and not all of them believed that ether—the fifth essence—really existed). Pythagoras said that cold ether was air, dense ether the sea and water in general. The soul, according to him, was also a part of the ether, whether hot or cold, and it (the soul) was invisible, because ether is invisible.... But Pythagoras lived two whole centuries before Aristotle.

Another ancient Greek philosopher, Chrysippus, who lived about three centuries after Pythagoras, believed that the whole world was a living being, animate and rational, and that its leading component is the ether. But this ether, it seems, was identified by Chrysippus, with some higher kind of fire. Hence, it was not a basic element of nature, but rather a sort of subelement.

The Roman poet and philosopher, Titus Lucretius Carus, understood the ether to be fine matter, consisting, like all matter, of atoms and whose flow sets all the celestial bodies into motion. He also thought that ether was a component of the soul.

In a word, even after agreeing that ether exists as a special substance and fills universal space, scientists from most ancient times could never agree on the definition of this substance. Two and a half thousand years have passed since the word "ether" became an entry of the scientific and near-scientific vocabulary. During these centuries, opinions on its properties have drastically varied. Only one of these properties has remained unchanged: the property of provoking heated arguments. As a matter of fact, ether has preserved this property "posthumously":

disputes still continue, even though for modern physics as a whole, ether is a concept antiquated and obsolete.

An Answer to All Problems

Antiquity bequeathed its ether to the Middle Ages, and in the European science of those times, ether was dealt with according to Aristotle, as the quintessence, the fifth element, the most profound essence of everything in nature. The far-famed French writer, François Rabelais, who was also a philosopher and naturalist, published his "Inestimable Life of the Great Gargantua" using the pen name "Alcofribas Nasier, Abstractor of the Quint-Essence". The search for this substance was a very fashionable occupation in those days, regarded as a much more dignified pursuit for true philosophers than looking for the philosopher's stone. Some of these searchers, incidentally, believed this stone to be the quintessence.

What debates raged in those days around the ether! Their scholastic nature should not give rise to a mocking attitude towards them. Such arguments perfected the capacity for reasoning. Thanks to the scientists of the Middle Ages, at least a part of the ancient heritage was still in circulation up to the Renaissance.

This was a period in which the Humanists actually did revive many propositions of ancient Greek science, which had gone out of use, and put them back into circulation again.

The ether of Giordano Bruno at the end of the 16th century resembles the ether of antiquity. It is again a fine, universal material permeating everything and enclosing everything. Some scientists called their universal matter "the boundless air". Ether in animate creatures was what they called the vital spirit.

Ether was frequently resorted to when it was necessary to explain a newly discovered phenomenon or to revise old explanations for long-known phenomena. One of the first investigators of electromagnetism, the court physician of Queen Elizabeth I, William Gilbert, reached the conclusion that ether flows out of electrified bodies and it is also what propagates heat. As to Galileo Galilei:

bodies exist and do not disintegrate into fine component parts primarily because their particles are held to one another by the pressure of the ether.

But the true renovator of the ether hypothesis, compared to antiquity, was René Descartes, champion of the Torricellian vacuum and opponent of simple emptiness, emptiness in general.

Absolute emptiness, declared Descartes, is impossible, because extension is an attribute, an indispensible feature and the very essence of matter. Consequently, everywhere where there is extension, that is, space itself, there must also be matter present.

There are three kinds of matter, contended Descartes, consisting of three types of particles: earth, air (the sky) and fire. These particles differ in their fineness and their motion differs. Since absolute emptiness is impossible, any motion of any particle brings others into their former sites, and all matter is in continuous motion, forming a great many rotational vortices with the most diverse properties (true, isn't it, that this strongly reminds one of the reasoning of Plato in his "Timea"?).

From this follows a multitude of consequences, but the chief conclusion is: all physical bodies are the result of vortex motion in an incompressible and unexpansible ether.

Descartes' hypothesis, a very elegant and spectacular one, had a vast influence on the further development of science. I would not hesitate to affirm that this influence remained even after certain principal propositions had been explicitly disproved. It soon became clear that these propositions do not, in the main, coincide with what follows from laws discovered somewhat later by Newton and other physicists. According to Descartes, for instance, the earth should be elongated along its axis and not flattened at its poles as it is supposed to be (and actually is) according to Newton. Tests showed that Newton was right. Other examples of the same kind were found.

The idea, however, of conceiving bodies (and then particles) as certain vortices, or coagulations, in a finer medium, turned out to be very tenacious or, even better, viable. And even today hypotheses are discussed in which elementary particles are regarded as certain vortices, though not immersed in ether. Whereas the idea that elementary particles are to be conceived of as excitations of vacuum is now recognized by many physicists as a scientific fact.

Descartes' version of the ether quite soon quit the physical stage because it was so much more "philosophical" than "physical". This speculative invention of this great Frenchman was called upon to explain almost everything in the world out of hand, and to mark off all the lines that form the drawing of the universe.

But physicists were interested in more "particular" problems, like the nature of gravitation, laws of light propagation, etc.

These problems could be solved so conveniently, it would seem, by applying the hypothesis of an ether, not necessarily in the Cartesian form, perhaps, but in a revised one suitable for solving some specific problem.

But scientists of the 17th through the 19th centuries, who had accepted ether to be the universal medium, found themselves from the very beginning in a tight corner. They, in contrast to ancient philosophers or scholastic scientists, were representatives of the new science based on the principle of Francis Bacon: proper experimental tests of all theoretical propositions.

Sufficiently convincing arguments were quite enough, from the point of view of Pythagoras, Aristotle, or Chrysippus, to describe the ether in minute detail. But could this satisfy the scientists of newer times, such men as Newton, Laplace or Mendeleev?

The opinions of Newton on the ether are doubtlessly worthy of especial attention.

> The great materialists of ancient civilization had indeed postulated the reference of all material phenomena to a process of atomic movements controlled by rigid laws, without appealing to the will of living creatures as an independent cause. Descartes, in his own fashion, had revived this ultimate conception. But it remained a bold postulate, the problematic ideal of a school of philosophy. In

> the way of actual justification of our confidence in the existence of an entirely physical causality, virtually nothing had been achieved before Newton.
>
> *Albert EINSTEIN*

Newton's ideas on the ether were complex, quite difficult and even tragic. Their history combines the history of the struggle against the very concept of an ether and the struggle for the recognition of this concept. Newton sometimes affirmed and sometimes denied the existence of ether as a universal medium. To reduce this matter to denial or affirmation does, indeed, extremely oversimplify the matter and allays the tense feelings that were aroused. Nobody calls a hurricane a gentle breeze or a desert a quiet refuge. But whatever the similes and epithets we choose, believe it or not, they may be insufficient to express the profound emotional nature of Newton's views on the ether.

At different periods, this eminent physicist held three basic views.

First: the sun, planets and stars are surrounded by absolutely nothing. This nothing is what fills universal space.

Second: space is filled with a kind of matter, some material medium. This is not nothing, but something about which it is better not to guess, because of the unavailability of the required experimental material ("I frame no hypotheses!").

Third: everything in the universe, from the emptiness between bodies and to the bodies themselves, is permeated with the finest particles of ether.

"Within" the last of these propositions, we can separate out two more, somewhat different from each other. According to the first (let us call it "third alpha"), gravitation and light are associated with the ether. But in "third beta", gravitation has nothing to do with the ether. Light, as well as all short-range interactions of bodies and many vital processes in all animate organisms, was quite another matter.

It is, however, difficult to find any rigorous, any regular sequence, some kind of order, at least chronological, in the way this great scientist adopted and changed such opinions during his long lifetime. He accepted one or another idea, then rejected it, then returned to it again, and again found new objections. Indeed, he was not like the media stereotype of a scientist that is someone who is possessed by a single idea, devoid of doubt and achieves his aim notwithstanding the criticism and doubts of his associates. Newton so feared criticism that he sometimes hesitated to publish his most brilliant works and could sometimes question his own ideas no less intently than his opponents.

In 1672 Newton proposed a memoir called *The New Theory of Light and Colours* to the London Royal Society. Historians of Science are inclined to consider this the first, not very definite statement in favour of the concept of light as a stream of certain material particles or corpuscles. But Newton's contemporary and violent opponent Robert Hooke understood everything "perfectly" and with his customary quick temper opposed Newton's corpuscular hypothesis with his own wave hypothesis*. Light consists of waves, he insisted, which propagate in a medium of universal ether.

Some time passed, after which Newton, becoming more and more convinced of the "material" nature of light, seemed to be ready to agree that vibrations of the ether are equally useful and necessary for both the wave and corpuscular hypotheses.

It seems that we have here a point of view corresponding to the one we have called the "third position".

But how could someone whose motto was "I frame no hypotheses" have believed in the existence of an ether?

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* By this time the Italian mathematician and physicist Francesco Maria Grimaldi (17th century) had already written about light waves. At the end of the seventies of the same century, the famous Dutch scientist Christiaan Huygens was engaged in a detailed development of the wave theory of light (also arguing against Newton). In 1690 his main work devoted to this problem was published. The contribution of Huygens to the wave theory was so extensive that he is deservedly recognized as its founder. He was first to shape guesses and assumptions into true scientific form; he furnished a profound and comprehensive basis for the idea.

He did not even care for theories (i.e. hypotheses extensively confirmed by experiments). Only the scientific propositions to which he conferred the noble name of "truth" could satisfy this exacting intellect. For Newton, "whatever is not deduced from the phenomena, is to be called an hypothesis; and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy." He added that hypotheses should conform to the nature of phenomena rather than attempt to subordinate it to themselves, bypassing experimental proofs. He said that if somebody advances a hypothesis only because it is possible, he could not see how in any science anything could be established with any accuracy.

As a matter of fact, Newton proposed hypotheses only in our modern, but never in the scholastic meaning of the word. His hypotheses were based on precise observations and rigorous experiments (not implying, however, that all such propositions turned out to be necessarily true).

The ether was necessary and of benefit to Newton's theory. But this is hardly enough to recognize that the ether exists. Newton could not renounce his principles. And he warned that in expounding the hypothesis of an ether, he sometimes "speaks of it as though he has accepted its existence and believes in it", but that this is only "to avoid verbosity and for a clearer conception". The hypothesis of an ether is feasible and no more. And this being so.... Return two paragraphs and reread Newton's ideas on hypotheses.

Thus, most likely there is no ether; it is an interesting hypothesis and only a hypothesis, but we know how Newton regarded this term. In 1704 in his *Opticks*, he makes no mention at all of the ether hypothesis, and this happened after his recent statement on the "benefit" of ether vibrations for any theory on the nature of light. In 1706, in the second edition of his *Opticks*, the world of scientists, which held the opinion of its recognized leader in high esteem, read, "Are not all hypotheses erroneous in which light is attributed to pressure or motion propagating through a certain fluid medium?"

This line of reasoning coincides with the "first position" of Newton in our conditional classification.

But in 1675, Newton wrote that if we assume that light beams consist of small particles, emitted in all directions by luminous bodies, then these particles must inevitably excite vibrations in the ether. And here only the idea of particles of light corpuscles seems to be the assumption, whereas the ether is something indisputable, even though it does not lend itself to detailed description. This is the "second position".

In a letter written in 1679 to another famous English physicist, Robert Boyle, Newton discusses his proposition of an all-pervading fine substance called the "aether". It varies in density and consists of "fine" particles, fine to various degrees. The closer the body (any body) to the centre of gravitation, the finer and finer the ether particles filling the pores of the body, expelling from them the coarser and larger ether particles. This motion of the ether is what makes the body strive toward the centre of gravitation and thereby causes it to fall to the earth.

Such reasoning obviously seemed too conjectural for Newton. In his general work on universal gravitation (though not only on this subject), the *Mathematical Principles of Natural Philosophy*, published in 1687, this assumption of the ether was omitted. But, for some reason, it again appeared in the third edition of *Opticks* which deals, in general, not with gravitation but with problems concerning light.

This position is what we have classified as the "third alpha".

At the end of the second edition of the *Mathematical Principles of Natural Philosophy* (1713), usually referred to as the *Principia*, Newton took the position we called "third beta". He wrote: "And now we might add something concerning a most subtle spirit which pervades and lies hid in all gross bodies, by the force and action of which spirit the particles of bodies attract one another at near distances, and cohere, if contiguous; the electric bodies operate to greater distances, as well repelling as attracting the neighbouring corpuscles; and light is emitted, reflected, refracted, inflected, and heats bodies; and all sensation is excited, and the members of animal bodies move at the command of the will, namely, by the vibrations of this spirit, mutually propagated along the solid filaments of the nerves, from the outward organs of sense to the brain, and from the brain to the muscles. But these are things that cannot be explained in a few words, nor are we furnished with that sufficiency of experiments which is required to an accurate determination and demonstration of the laws by which this electric and elastic spirit operates".

Gravitation, as you can see, is not even mentioned here, it is left strictly alone. Gravitation, for the sake of which Newton formerly resorted to the idea of ether, has no relation to it whatsoever. The paragraph would seem to be unworthy of this great scientist or his methodological principles. He expounds a hypothesis without ever mentioning the fact that it is one, although he acknowledges the scarcity of experimental data in this field. But....

Let us look more attentively into what Newton states here, forgetting for a moment all the definitions of ether that were given in his time, and accepting the term itself as the designation for something unknown, a certain x. It is then readily evident that all the phenomena for whose explanation Newton used the ether, we attribute today to the electromagnetic interaction of particles and bodies. It is what binds atoms and molecules together, produces light, and action currents play an exceptionally vital role in transmitting signals from the organs of sense to the brain and from the brain to the muscles!

All these diversified phenomena have been brought together on a common basis with an astute guess that is characteristic only of a genius. The unifying basis here is called the ether, but the point is not in the name....

Let us now return to the ether as a universal medium in the concepts of the 17th century. From time to time Newton simply notes that there is nothing known for sure about such an ether, nobody is even positive that it exists and, consequently, he, Newton, has no desire to even express his opinion on the subject ("second position").

After which he nevertheless does state his opinion, time after time, and it is sometimes for the existence of aether, sometimes against.

When Sergei Smirnov, a Soviet mathematician with an interest in the history of science, specially investigated the complex relations between Newton and his aether, he reached an interesting conclusion.

Ether was an immeasurable entity, one of those against which this famous Englishman objected flatly and especially consistently. Time after time he (Newton) underlined that he was investigating not even the kinds of forces and their properties, but only their magnitudes and the mathematic "relations between them". He was always interested in what could be determined by experiments and measured by numbers. His famous "I frame no hypotheses!" signified a decisive refusal of conjectures not confirmed by objective experiments. But, in the given case, Newton did not display such consistence. Why? "We find nothing about this," writes Smirnov, "either in his books or his letters. But, fortunately, memoirs of his friends are available. And they clear up a simple matter: Newton not only believed in God, Omnipresent and Omnipotent, but could not conceive of Him otherwise than as a special Substance permeating all space and regulating all forces of interaction between bodies and, thereby, all the motions of bodies, in fact, all that happens in the world. That is: God is the Aether! From the viewpoint of the church, this was heresy, whereas from the viewpoint of Newton's 'programme of principles' it was an unnecessary conjecture. But Newton (a good Christian and a good physicist) dared not write about this, his belief, but only sometimes said too much in friendly conversations. Poor Sir Isaac!"

Newton's chapter in the history of the concept of "ether" is doubly of interest. The immense prestige of Newton added prestige to ether as well. His contemporaries and their descendents paid much more attention to the statements of the famous physicist that confirmed the existence of ether than others questioning this existence.

> There are brilliant errors that have a stimulating effect on the minds of whole generation. First they are carried away by the errors and then take a critical stand against them. This enthusiasm and the subsequent criticism serve long as a school for mankind, an incentive for intellectual conflict, an occasion for the development of forces, a leading and colourful source of historical movements and upheavals.
>
> *Dmitri PISAREV*

The famous Dutch physicist, Christiaan Huygens had need of ether for purely scientific purposes: as a medium through which light waves could travel. Newton's theory of light had less need of such a medium, or none at all, because, according to Newton, light consists of particles, or corpuscles, that could, if necessary, travel through an emptiness as well. But if light consists of waves, thought Huygens, something must necessarily be doing the waving.

He reasoned much as in the following.

If we place the most ordinary bell under a glass dome out of which all the air has been pumped, there is no sound that any observer bent over this small device can hear when the metal clapper hits the side of the bell. Sound requires a medium to transmit its waves. It seemed that the same could be said of light. It is only that the waves of sound in air are produced when layers of air are consecutively compressed and dilated. But ether, carrying light, is, according to Huygens, absolutely incompressible, its particles transmit their motion to adjacent ones. As a result, the velocity of light should be infinite.

Huygens wrote: "There is no such thing, in the ordinary meaning of the word, no such body that travels from the sun to the earth, or from a visible object to the eye. There is a state, motion, or perturbation that was first at one place and then at another". Ether, in his opinion, also fills the spaces between the elements of ordinary matter; this could explain the transparency of certain substances.

Ether was frequently a favourite topic of discussion among many other scientists of the 17th and 18th centuries. In contrast to Newton, they did not, however, consider it to be God, but did hold it to be the cause of a great many natural phenomena.

A representative of the Dutch-German-Swiss family Bernoulli (a family that has given the world so many scientists that even today Roman letters follow their first names like those of kings), Jacob I Bernoulli supposed that gravitation can only be explained by ether, a fine elastic fluid. It is not only between bodies, but in them as well. He contended that it is precisely this ether liquid that makes solid bodies such as they are, because it permeates their pores, withstanding external pressure.

Johann Bernoulli, another eminent member of the same family, explained by means of ether such a phenomenon as elasticity. He held that ether vortices continuously tend to spread the solid particles, hindering attempts to change its shape.

At that time everything caused by gravitational or electromagnetic forces, as we now know, was blamed on the ether. But, since the other fundamental forces of the world were practically uninvestigated before the foundation of atomic physics, scientists undertook to explain any phenomenon and any process by means of ether. Too great a burden was put, too extensive problems were entrusted to Aristotle's fifth element. Even a real substance could not have justified such hopes, and would ultimately disappoint its advocates and investigators.

Sometimes, the most ordinary simple earthly air was taken to be the ether. A Soviet historian of science, V. P. Zubov wrote that up to the 17th century "most of the functions of what was later to be called ether were attributed to air", in physics and medicine of the Middle Ages. The inertia in thinking had propagated such a concept, in spite of Newton and Huygens, to the 18th century as well. In any case, the famous French encyclopedia, that brilliant codex of knowledge compiled in the middle of the 18th century, had in the entry "Air" reported the following: "Dr. Hooke believes this* to be none other than ether, a liquid and active material, spread throughout space in the heavenly regions. . .."

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* the air.

This is, of course, simply a historical curiosity, indicating to what degree an encyclopedia can sometimes be behind the science of its time. But this curiosity is a good illustration of the difficulties encountered in clearing up what, after all, ether was supposed to be.

As to science, Huygens' theory gave the concept of ether a truly new life. New to such a degree that in a large number of later scientific works, the term "ether" was employed mainly with the indispensible adjective "luminiferous" ("light-carrying") or "luminous". And this ether belonged in the 17th century and almost to the end of the 18th century to a strange trinity of those days. On equal terms with caloric (thermagen) and phlogiston, ether was one of the invisible, unobservable, weightless fluids, devised to explain a great number of natural phenomena, from heat to combustion and from light to gravitation. Strictly speaking, far more "weightless ones" were thought out than three. Simply these three were the most significant, most important for an understanding of the world we live in.

The blows that were dealt to the weightless fluids and similar substances by the ideas and experiments of Lomonosov, Lavoisier, Laplace and other physicists and chemists drove these fluids from the pages of textbooks into volumes devoted to the history of science. But this did not happen to ether at that time. And it could not yet take place! Physics and chemistry devised experiments that could check the hypotheses of phlogiston and caloric. As to ether, the engineering techniques of the time were too crude to even enable suitable experiments to be proposed. And what cannot be checked can only be taken or not taken on trust.

Each new triumph of the wave theory of light required that ether be endowed with newer and newer properties. This on the one hand, whereas on the other there were no experiments that could enable the existence of ether to be denied.

Little by little, however, the explanation of light phenomena on the basis of the ether hypothesis began to look more and more artificial.

When the English scientist Thomas Young and the

French physicist Augustin Jean Fresnel came to the conclusion that light consisted of transverse vibrations, rather than longitudinal ones, it was difficult for them to understand the result as being real. The vibrations were taking place, in their knowledge, in an ether liquid and the properties of liquids are not at all suitable for such vibrations.

To provide for motion of transverse light waves at a velocity that was determined with sufficient accuracy as far back as the 17th century, ether would have to have a fantastically high elasticity. Higher than that of the most elastic steel. (The higher the velocity of waves, the more elastic must be the substance through which they propagate.) But elasticity is primarily a property of solids, and not even any solid at that. At the same time ether did not hinder the motions of the stars and planets, and, with respect to light, was more transparent than any gas.

The British mathematician and physicist George Gabriel Stokes compared ether in 1845 with tar and cobbler's wax. These substances are sufficiently stiff for rapid elastic vibrations and, at the same time, can allow solids to pass through them.

What could be expected from the scientists that accepted the ether theory, but to try on the properties of all familiar substances? Sometimes these were gases, sometimes liquids and sometimes even solids.

"If we wish to comprehend the action of the so-called weightless fluids, we should compare them with materials that are closest to them, and that can be understood directly, not only by their concealed distant effects." Thus in 1824 did Christian Heinrich Pfaff, Professor of Medicine, Physics and Chemistry in the Kiel University formulate his principle in dealing with imperceptible substances.

The basic principle of this approach appears to be correct. Physicists of the 20th century employed, and even today frequently employ, a model of an atomic nucleus in the form of a drop of an electrically charged liquid. Such a model proved convenient sometimes in calculations concerning the decay of heavy nuclei (drops can also break up). Under other conditions, an atomic nucleus is often likened to a gas bubble, etc. But physicists of our time never, for even a second, forget, in applying such models, that actually the nucleus is neither a gas, nor a liquid, nor a solid.

> It is most instructive to admit that even single assumptions or hypotheses, which later were found to be incorrect, have time and again been the cause of important discoveries, enhancing the power of science. This occurs because only the general ideas, presenting themselves to our minds as truth, i.e. hypotheses, theories and doctrines, provide the persistence, even stubbornness in investigation, without which sufficient perseverance could not accumulate.
>
> *Dmitri MENDELEEV*

Newton's old principle: to study the magnitudes of forces and their relations, without hurrying to clear up their nature and properties, a principle that is so hard to follow, was deeply buried in oblivion by science with respect to the ether. This was perhaps just; science was in a stage of development and was entitled to methodological innovations. But, in the case of ether, many physicists permitted themselves undue license even from the viewpoint of the science of their time.

Scientists of the 17th, 18th and 19th centuries certainly had a right to the hypothesis of a material medium filling all space. But they had no right to endow this medium with properties that would explain everything that required an explanation.

Finally, it is necessary to pay especial attention to the major role the idea of an ether played in world unity for binding together the parts of the universe. For hundreds of years ether served many physicists as a means in their struggle against the possibility of action at a distance, against the idea that a force can be transmitted from one body to another through a void. Even Galileo was sure that energy is transmitted from one body to another upon direct contact. This principle is the basis for Newton's laws of mechanics. Meanwhile, the force of gravity, it turned out, seemed to act through empty space. Hence, scientists reasoned, it should not be empty; hence, it should be completely filled with certain particles that transmit, exactly like a relay race, forces from some celestial bodies to others, and even by their motion provide the operation of the law of universal gravitation.

In the middle of the 18th century, the Swiss physicist Georges-Louis Lesage proposed an exceptionally simple and extraordinarily attractive hypothesis that explained Newton's law of gravitation by the effect of special particles of ether. Newton's ether simply tends to approach the centres of gravity, carrying along the bodies it penetrates, whereas Lesage's particles pushed any bodies toward one another.

The trouble with this hypothesis is that it can be readily checked by calculations. Indeed, in an "ether gas" of such particles, the universal law of gravitation would operate exactly according to Newton, but in such a gas the earth itself would be slowed down in its motion on its solar orbit. Quite soon it became clear that our planet would, in such a case, have long ago lost its "reserve of velocity" and, consequently, would have fallen into its maternal star.

Nevertheless, this hypothesis was extremely graphic; it proposed a much too effective model of gravitation to be discarded so quickly and so finally. Modifications of Lesage's idea are still being proposed, literally up to our time. Their originators sometimes advance quite ingenious methods to conserve for our planet (and all the others) the possibility to keep travelling along its orbit. But each new version of Lesage's idea always reveals its weak points; facts are always found that contradict such hypotheses.

It is of interest that many advocates of ether believed that on the basis of a further investigation of this substance, even the formula of universal gravitation could be given a more precise form. In his book *Newton and His Time,* the Soviet scientist I. Yu. Kobzarev wrote on this matter as follows: "...Deviations from Newton's law were desirable, it seemed natural that such a strange unfounded law could not be exact; hydrodynamics of the ether should yield something more complex."

In the 19th century the idea of an ether became, for a time, the theoretical foundation for the actively developing field of electromagnetism. Evidently, Michael Faraday, the English physicist, vaguely felt, at times, something resembling aversion, and made attempts to do without this strange substance which could not be either weighed or measured. But what could be done? No other concept could, at that time, be of any aid whatsoever. Consequently, electricity began to be dealt with as a certain fluid that could be identified only with ether. It was emphasized in every possible way that the electric fluid is the one and only such substance. By that time, the most outstanding physicists could no longer reconcile themselves to a return to many weightless fluids, though the problem in science of the existence of several ethers (or that ether is diversified) had been raised from time to time.

Up to the last decades of the 19th century, it could be said that ether was universally recognized. There were already almost no arguments as to whether it really existed. Just exactly what it was was quite another matter. Essentially, several versions of ether competed with one another.

In one case the earth passed through the ether or, if you like, the ether through the earth, which was transparent to the ether. In another version, the particles of ether "pushed" our planet because they could not pass through it.

Sometimes ether was made to obey the law of universal gravitation; sometimes it was released from its sovereignty.

The eminent British physicist William Thomson, better known as Lord Kelvin, constructed a model of the ether out of rotating particles, or "tops". He was looking for a mechanical system that would resist only deformation accompanied by rotation. In one version he had liquid tops, in another, solid tops. In still another model proposed by Lord Kelvin, ether was simply an incompressible fluid.

Lord Kelvin was absolutely convinced that ether existed, because only such imperceptible matter with the properties of a gas, a liquid and a solid could provide an explanation for any phenomena by means of the laws of mechanics. These were the laws, he believed, that lay at the basis of all natural laws.

Lord Kelvin once said that it seemed to him that the real meaning of the question: do you understand such and such a physical situation? should be the following: can you devise a corresponding mechanical model? He said that he was never satisfied unless he could conceive of a mechanical model of a given phenomenon. If he could imagine such a model, he understood the problem; if he could not, then he didn't understand it.

James Clerk Maxwell also required a mechanical model in working out the explanation of electromagnetic action. According to Maxwell's constructions, a magnetic field is set up because it is produced by tiny ether vortices, somewhat like thin rotating cylinders. To keep the cylinders from contacting one another and hindering their rotation, the finest of spheres, also in rotation, were inserted between them as a kind of lubrication.

The vortex cylinders were of ether, as were the vortex spheres, but the latter had already been named particles of electricity. ("...One would think he is reading a description of some industrial plant with a whole system of gears and levers, transmitting motion and distorted by forces, centrifugal regulators and transmission belts", wrote Jules Henri Poincaré, the French mathematician and physicist, of his impressions of Maxwell's works.)

This model was complicated, but it did demonstrate by customary mechanical means many typical electromagnetic phenomena. It is frequently and justly said that Maxwell formulated his famous equations on the basis of the ether hypothesis. But the attitude of Maxwell to models of this kind differed from that of Lord Kelvin. It is therefore probably not worthwhile to exaggerate the significance to Maxwell of the ether model of electromagnetism, or the idea of ether as such. About the former he noted in a letter that the model of a phenomenon is to the true phenomenon as a clockwork model of the solar system would be to the system itself.

As concerns the idea of an ether, for Maxwell, profoundly convinced of its reality, the ether was perhaps a medium having many more hazy properties than those conceived by the majority of his contemporaries.

In return, after discovering the fact that light is merely a variety of electromagnetic waves and that any electromagnetic oscillations are transverse, Maxwell treated "luminiferous" and "electrical" ethers as being identical. Previously, they had existed in the theory as parallel and independent entities. This led to the conclusion: light consists of the same transverse oscillations of the same medium that is the cause of electrical and magnetic phenomena.

At the turn of the century, the concept of a universal ether permeated world science no less deeply than the ether itself, according to these concepts, permeated the universe.

Dmitri Ivanovich Mendeleev wrote the following about ether for the Brockhouse and Efron Encyclopedia in the entry titled "Substance": "It is necessary to assume that the known position of the solar system in the midst of other systems of the universe, like the positions of the various planets in the solar system, is determined, not only by inertia, but by an intermediate medium that transmits light and has a special state of elasticity resembling that of solids. In exactly the same way for real matter, built up of atoms and the particles they form, it is necessary to assume the participation of not only inertia, but of that translucent universal medium that is only weightless because it permeates all things as air is weightless in air and turns out to be really ponderable only when it proves possible to eliminate it. It is not possible to eliminate the universal medium: a void, absolutely deprived of the universal medium, is impossible to attain."

On the other hand, this famous chemist understood that the idea of ether as a universal medium, is not coordinated with firmly established and rigorously proved theories as closely as many scientists believed in those days.

In one of his papers he especially stipulated: "The concept of chemical elements is most closely associated with the generally accepted theories of Galileo and Newton on the mass and ponderability of matter, and with the doctrine of Lavoisier on the eternity of matter. The concept of an ether is called for exclusively by the investigation of phenomena and the need to reduce them to simplest notions." Further on he wrote again that the "luminiferous ether, if it is real, is ponderable...". In other words, he admitted the possibility that ether is not real.

The ideas of Mendeleev on ether were on a level with the knowledge of his time. He tried to raise this level, in particular, by approaching the problem of a universal ether as a chemist. He tried to find what known substances on earth could resemble ether. It stands to reason that though its elasticity resembles that of solids, a comparison suggests itself with gases. With which one? With the inert gases or, as he wrote, "with the argon gases because they do not react with any elements. The universal ether, though permeating all bodies, also does not react chemically with them."

If the gas-ether is assumed to be an analogue of the gas helium, then, on the basis of this similarity, we can try to surmise what the ether atom should be like. We shall employ the same, in essence, method that Mendeleev used to find the properties of yet-unknown elements. We know what brilliant success he achieved with such predictions. In reasoning along these lines about the ether atom, Mendeleev entered regions to which the laws of chemistry had nothing in common (nor did the physics of those days, before the advent of quantum mechanics, have methods by means of which it was possible, even partly far from comprehensively, to describe a physical vacuum).

Nevertheless, Mendeleev's search for the "ether atom" remains of interest to this day. And not only because it was undertaken by the famed "Mendeleev himself". Keenly interesting is the method he employed.

Mendeleev came to the conclusion that the square of the velocity of an ether particle should be as many times greater than the square of the velocity of a hydrogen particle, "as the density of hydrogen exceeds that of ether at equal temperatures".

Adopting for universal space, in accordance with the views of his time, a temperature of 80 °C below zero, Mendeleev, on the basis of a simple proportionality, found the minimum average velocity of the ether particle to be 2000 km/s, and the atomic weight of ether to be "not far from 0.000001" (one millionth).

An article by V. Khramov was published in the Soviet journal "Chemistry and Life" on this assumption of Mendeleev. After replacing the obsolete data in the calculations of the famous chemist, correcting, for instance, 80 °C (in free space) to 250 °C below zero, Khramov obtained for the Mendeleev ether atom an atomic weight of one billionth, corresponding to a mass of 10^{-33} gramme. This is six orders of magnitude less than the mass of an electron (about one millionth).

Khramov writes, "...the special theory of relativity... did away with 'universal ether' only as some fixed medium, capable of serving as an absolute frame of reference. But Mendeleev, in essence, only suggested that there exists an as yet undiscovered minimal particle of matter (now we would call it an elementary particle), similar to the noble gases in its inertness *, ... omnipresent and omnipenetrative... Was Mendeleev so very wrong?"

The question on which this quotation ends is, of course, quite rhetorical. Khramov answers it by trying to identify the ether atom with the "undetectable" (though now detectable) neutrino. It "also" extremely weakly reacts with substances and has an insignificant rest mass.

In a recent experiment (conducted about three years after the publication by Khramov), that still requires confirmation, the rest mass of the neutrino was found to be from 14 to 46 eV. This corresponds to about 10^{-32} gramme. This is quite a good coincidence with the Mendeleev-Khramov ether atom!

Doesn't it seem (from our distant look) that Mendeleev's premises, in the given instance, were absolutely untenable? Yes, but is this the first time in history that genius has plucked a golden apple of discovery while standing on a good-for-nothing ladder? More accurately, one good only as a ladder or pedestal to pluck only this particular apple. Johannes Kepler, for instance, attribut-

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* Inert in the chemical sense.

ed free will to the planets, but this did not hinder him from formulating the laws that actually govern the motion of planets.

As a matter of fact, most physicists are not likely to agree with the conclusion of Khramov's interesting article. What of it? It was still of benefit to relate this short episode to give the reader an idea of the permeation of all the natural sciences by the idea of ether at the turn of the century.

Grandeur and Fall of the Ether

The well-known *History of the XIX Century*, published in France, edited by the French historians Ernest Lavisse and Alfred Nicolas Rambaud and translated into various languages, states: "In general, at the end of the 19th century, physics evidently hesitated between two essentially different conceptions. One, in explaining facts, preferred interactions of ponderable molecules; the other regarded these molecules to be inert and saw, in the weightless ether, an inexhaustible container of natural forces and energies, a factor capable of producing them at our desire in the most diverse and unexpected forms."

> Science has no eternal theories. It so happens that certain facts predicted by theory are disproved by experiments. Any theory has its period of gradual development and triumph, after which it may be subject to rapid decline.
>
> *Albert EINSTEIN*

The eminent Dutchman Hendrick Antoon Lorentz, himself an advocate of ether, after analyzing the principal versions of scientific hypotheses associated with ether and advanced in the 19th century, sorrowfully stated: "These theories had a certain success, but it must be acknowledged that they do not give much satisfaction; they become more and more artificial with the increase of the number of cases requiring detailed explanations".

Remarks of this kind could not, however, repudiate the "principle of ether" itself. The authority of Newton (even if he was wrongly understood) and Huygens was enforced by the opinions of others who were the greatest among the great, such as Faraday and Maxwell, Kant and Mendeleev. Even Newton's law of universal gravitation had perhaps no greater influence on the intellect than this staggering concept of finest matter, joining the universe into inseparable unity, providing science with something absolute, a place to start from or, in more scientific language, a reference frame.

According to the British physicist, John Tyndall, the majority of scientists were convinced of the existence of ether no less than of the existence of the sun and moon.

As long as ether was the same kind of speculative construction as the void of Democritus, it could withstand any onslaught of skeptics. But when it was entrusted with specific and difficult duties, the situation changed drastically. All the more so because the number of these responsibilities increased with the development of science.

Judge for yourself: ether had to provide for the action of the law of universal gravitation (as a transmitting link in a mechanism developing an unknown force or as something that generates such a force); ether was the medium through which light waves travelled; ether assumed responsibility for all manifestations of electromagnetic forces; and, in general, answers to almost all riddles of nature, whether physical, chemical, or biological, were to be found in ether.

For simultaneous accomplishment of all these functions, ether had to have extremely diverse and frequently quite contradictory properties.

> The folly and wisdom of each age are equally valuable for the science of subsequent ages.
>
> *Stanislaw Jerzy LEC*

The concept of an ether could not be rejected in ancient science even because it could not, as we know, be put to the proof by either calculations or experiments.

Modern science has at its disposal both of these powerful means.

They liked very much in Ancient Greece to ask questions which were such that they are still difficult to answer twenty-five centuries later.

Modern physics also likes to ask itself questions, but not any kind. They must be questions that can be defined as well-posed ones. As a matter of fact, the definition was derived by science itself. This does not imply that there is a ready answer to all well-posed problems. It only follows that such answers can, in principle, be obtained.

Just what does this mean? M. A. Markov, member of the USSR Academy of Sciences, wrote: "Physicists consider that questions should be addressed to them approximately as follows: 'What will be observed if I do so and so?' If the theory is correct and comprehensive, it should answer any such question, and answer it in the form of definite scientific foresight."

A theory whose scientific foresight does not come true without any valid reasons, falls into the category of non-viable ones and is duly buried. If it had any previous merits, it is buried with honours, but not too splendid ones at that.

To remain viable, a physical theory must comply with three conditions, meet three sufficiently clear-cut criteria.

In the first place, the theory should never lead to sharply contradictory conclusions. This necessary property is called self-consistency. A theory may dispute other theories but not itself.

Secondly, a theory must be able to explain all indisputable data of experiments conducted in the field it is responsible for.

Thirdly, the fundamental principles and laws on which the theory is based should enable it to carry out calculations for specific situations, and to analyze the results of any new experiment conducted in the field "controlled" by the theory.

Besides, the laws of the theory must be in agreement with the laws of all other fields of physics.

A theory provides the precious possibility of predicting facts that were not known to anyone when the theory was advanced. The coincidence of such predictions with the real facts becomes the criterion of the truth of the theory.

Predictions are soon made on the basis of a new theory, but if they do not prove to be true, then trouble begins.

These criteria were formulated relatively recently but, perhaps with insufficient insight, attempts were made to comply with them in the 19th and 18th, and even 17th centuries.

But the theory of the universal ether, even up to the eighties of the 19th century, could hardly be said to completely satisfy these criteria.

We have already mentioned that ether was found to possess mutually exclusive properties, so that its self-consistency was far from what it should have been.

In order to explain newly observed facts, to analyze new experiments, it was necessary to continually supplement the ether hypothesis, and these supplements became, in the opinion of physicists, more and more artificial.

True, a precise experiment to determine the very fact of the existence (or absence) of ether could not be conducted for a long time, if only because the ether, in different versions of the hypothesis, behaved in different ways.

In the opinion of certain scientists, ether justified Aristotle's translations of its name: "eternally in flight", other scientists believed it to be absolutely stationary. The German physicist Heinrich Rudolph Hertz, the discoverer of radio waves, insisted that travelling bodies drag ether along with them. The Dutch physicist, Hendrik Lorentz, on the contrary, considered ether to be absolutely at rest, and that the motion of bodies in it has no effect whatsoever on the positions of the ether particles. There were also "intermediate" hypotheses, according to which ordinary matter in its motion only partly entrains the ether.

At the beginning of the 20th century in Russia, Aleksandr Eikhenvald, later member of the Ukrainian Academy of Sciences, compared the views of Hertz and Lorentz and came to the following conclusion: "That which we call today the universal ether and which permeates all material bodies, should be assumed stationary even inside matter that is in motion". In a word, even in the 19th century, the concept that the ether was a stationary medium, the fixed background on which all existing bodies travel, triumphed.

Only when this conception was finally crowned with success (even though it was not acknowledged by all scientists), could the theory at last predict the result of a precise experiment. This gave the theory of ether the opportunity to prove its validity, or, just as likely, to disprove it.

The idea of the experiment had been outlined years previously by James Clerk Maxwell. It is extremely simple, though this eminent physicist evidently doubted whether it could be really conducted. He said that if the velocity of light could be measured by the time it requires to travel between two points on the surface of the earth and then the obtained data be compared with the velocity in the reverse direction, the velocity of motion of the ether with respect to these two points could be determined.

The first of the serious experiments to determine the velocity of the ether was conducted, as a matter of fact, not according to this outline, but faithfully followed its principle.

> The event
> Was accomplished
> But reason
> Had yet to absorb it entire.
> It hadn't burst hot from the lips yet,
> A tale like a swift-spreading fire.
> The moments were not yet near
> To assess it dispassionately,
> But nonetheless
> All was clear
> From the look of the earth and the sky....*
>
> *Leonid MARTYNOV*

In 1881, the *American Journal of Science* ran as an article a paper by Albert Abraham Michelson. The basic idea of this paper is concentrated in a short sentence in

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* Translated from the Russian by Alex Miller.

which he stated flatly that "the hypothesis of a stationary ether is thus shown to be incorrect".

This conclusion summarized the result of an amazingly elegant experiment. The American writer, Mitchell Wilson, wrote of Michelson: "Of all Michelson's contradictory qualities, the one that was most persuasive was elegance: elegance in technique, elegance in intellectual analysis of physical problems, elegance of presentation, and elegance of appearance".

To describe the basic scheme of the experiment I permit myself to make use of another quotation from Mitchel Wilson.

"The heart of Michelson's method depended on the same phenomenon that explained the iridescent colors seen in a thin film of oil floating on a puddle of water. Most of the sunlight is reflected from the upper surface of the oil film, while some of the light penetrates the film and is reflected from the lower surface. At certain angles, the two light reflections interfere just as water waves can cancel or reinforce each other depending upon whether the trough of one wave coincides with the crest or the trough of another. (The different colors that make up white light have slightly different wavelengths.) In the interference of light, some colors cancel and one sees a black streak on the oil; where the colors reinforce, one sees streaks of chromatically pure prismatic colors."

In Michelson's interferometer, a beam of light was also split in two, each of the new beams travelling its own path, and when they were joined anew, light and dark fringes were formed.

The young physicist decided to make use of his instrument to determine the velocity of motion of the earth in the ether. With the pressure they exerted, the particles of ether should have slowed down the velocity of the beam travelling in the direction of the earth along its orbit; the ether wind blew counter to this beam. The second beam was directed perpendicular to the first, that is, it did not travel counter to, but across the ether wind. Then the beams were united again by means of mirrors. A fringed interference pattern was obtained.

This was followed by swivelling the installation through ninety degrees. Now it was the second beam, not the first, travelling counter to the ether wind. This change should have led to a shift in the interference pattern (if there really had been an ether wind). The pattern remained fixed. Meanwhile the velocity of the earth along its orbit was about thirty kilometres per second and this is exactly the velocity that the ether wind should have had, and the amount it should have slowed down the beam of light travelling counter to the wind. Since this did not happen, there had been no ether wind.

In 1884 Hendrik Lorentz criticized certain details of Michelson's experiment; he indicated some shortcomings in the way the experiment had first been conducted. In 1887, Michelson, together with an American chemist, Edward Williams Morley, repeated the experiment in an improved version.

The interferometer was now mounted on a massive plate that floated in mercury for the purpose, in particular, of making the required swivel through ninety degrees as smooth as possible.

In the hundred years that have passed since then, by means of instruments designed on the same principles, it has been established that the ether wind does not even have a velocity of 1.5 km/s. Other techniques have not left it a velocity of even 50 cm/s.

Luminiferous universal ether it was called, light it carried, and light was to seal its fate.

The history of the science of light numbers thousands of fascinating pages, and hundreds of books have been written upon the subject.

In our age of the mastery of space and the numerous arguments it provokes as to whether this mastery justifies the expenditures it has led to, it might be of benefit to recall that the satellites of Jupiter, for example, proved to be of real assistance a few decades after they were discovered by Galileo. On the basis of the motion of the satellites and the shadow that one of them cast on Jupiter, the velocity of light was first measured in the 17th century. The error did not exceed several per cent.

It was so natural that, at the end of the 19th century, an experimenter, who had precisely measured the velocity of light without leaving our home planet, dealt the death blow to ether, which had been devised, in its time, for the sake of this same light.

It is most likely that Michelson was sure that the motion of the ether would affect the motion of his light beam. He conducted his experiment to confirm a generally accepted theory, not to disprove it.

An experiment, as has long been known, is wiser than the experimenter. We must, however, do justice to the scientific audacity of the physicist, his confidence in his brain and hands. In his statement of "the downfall of the ether", he challenged no more and no less than all of world science. Recall that Newton, fearing criticism (although not only for this reason), awaited almost eighteen years to publish his works on universal gravitation, and that Karl Friedrich Gauss, for the same reason, refrained from making public his work on noneuclidean geometry. And this notwithstanding the fact that both had won immense prestige in the world of science.

It was, perhaps, even easier for Einstein to challenge old doctrines. When his work was published, the foundation had already been laid for the theory of relativity.

What a stroke of luck, said one scientist, when a well-verified experiment contradicts a well-confirmed theory. One cannot say, of course, that the ether theory was well confirmed. But it was certainly recognized to the highest possible degree.

Thus a beautiful theory had been slain by an ugly fact. It had happened and was almost unnoticed for quite some time. Some theories turn out to be of rare vitality. The words of Alexander Pushkin: "A host of base truths to me dearer are/Than deception that ennobles one", is valid not only for poetry alone and not only in dealing with purely historical legends.

It would not be true to say that Michelson's statement made an impression like a bursting bomb. The bomb, of course, really did blow up, and it even scattered the fragments of the hypothesis that had long since been promoted to the rank of a theory. But the majority of the scientists had no wish for a long time to even take note of the explosion. Physicists from the world over highly appraised the perfection of experiments conducted by the same Michelson in determining the velocity of light in various media, including a vacuum. Delightful stories were told about how Michelson had made his first instrument for measuring the velocity of light when he was only twenty years old and held the rank of a naval lieutenant, and that the instrument had cost exactly ten dollars.

This ingenious experiment readily brought renown to Michelson. But real fame was in no hurry to reward his most distinguished experiment.

Historians of science suspect that Einstein, when working on his special theory of relativity, had not yet known of Michelson's experiment, whose result was one of the most important arguments in favour of the truth of Einstein's ideas.

The fact that a fact was not recognized deserves a thought (please excuse the tautology). Is it not too often in the history of science that the results of an experiment are disregarded until a theory is proposed that can explain these results? The results of an experiment that tests a competent theory are awaited much more impatiently than the proposal of a hypothesis that explains an already conducted experiment, which does not fit its previously allotted shelf.

Incidentally, this indifference of the physicists did not pass by the attention of the great scoffer George Bernard Shaw. Hesketh Pearson's biography *G.B.S. A Full Length Portrait* mentions that the Michelson-Morley experiment greatly interested Shaw. The great playwright was able to draw the proper conclusions from the experiment. According to Pearson, Shaw said that bang goes Copernicus, and Young's hypothesis of an ether pervading space, and the velocity of light, and the whole fabric of astronomical physics. Shaw said that it had not much to do with him because he had always denied that any mechanical experiment could make men believe what they did not want to believe, nor disbelieve what they wanted to believe.

Nevertheless, at least two eminent physicists, advocates of the ether theory, took note of the results obtained by Michelson and Morley. The Irish physicist George

Francis Fitzgerald and H. H. Lorentz in the Netherlands found, in their opinion, the possibility to save the ether theory*. It was sufficient to propose that bodies moving counter to the ether wind are shortened, with the amount of this "foreshortening" increasing as their velocity approaches that of light.

True, Hendrik Lorentz, with his high scientific punctiliousness and profound emotional attitude towards scientific truth, was very disturbed that this idea was devised, as they say, to rise to the occasion, specially to explain a specific experiment.

He wrote: "Inherent in such an introduction of a special hypothesis for each new experiment. . .is a certain artificiality". In other words, Lorentz was aware of the gap between his hypothesis and all preceding physical conceptions.

But he did advance his hypothesis! As it turned out, it correctly described the facts, but incorrectly explained them. Under the name of the "Lorentz-Fitzgerald contraction" this phenomenon is included up to the present day in physics textbooks.

The hypothesis was brilliant, the formulas proposed in it were splendid. Only the aim for the sake of which it was proposed could not be achieved. The "rescue operation" to save the ether fell through. Hence, the proposal itself, advanced by two scientists independently of each other, was really recognized by scientists only after the defeat of ether in its combat with the theory of relativity.

With all of its indisputable virtues, this hypothesis had one essential shortcoming. It endowed the ether with properties that made it literally invisible to science. Not only were no procedures given for determining the velocities of anything at all with respect to the "Lorentz ether", but, on the contrary, it was quite clear that such a procedure simply could not be found. This, of course, could not bring peace and quiet into the world of physics, which, way back from the time of Galileo,

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* Also to be named in this connection is the British physicist Joseph Larmor, who did research in this line.

had adopted the principle: verify all and everything. At the same time, physics had nothing so far to replace ether: there was no serious theory that could withstand the "ether" one.

Most scientists were fully confident that the time of the fifth element, having outlived all the other elements by hundreds of years, had not yet expired. Embarrassed as they were by recollections of the downfall of other "weightless" elements like caloric and magnetic fluid, it was very difficult for the scientists to admit that ether awaits the same fate.

Too beautiful (no irony meant) was the ether theory to allow some ugly monster—an experimental fact—to spoil it before being replaced by some other beautiful theory.

Michelson's experiment was repeated again and again in different versions. Sometimes the ether wind seemed to have been observed. True, subsequent tests again and again restored the windless or, to be more exact, etherless calm.

To this very day, incidentally, physicists who remained true to the old ether picture of the world continue to investigate Michelson's experiment. Maybe something was done wrong, some mistake slipped in; maybe there could be some way to explain why no ether wind was observed?

What if the experiment has been repeated so many times, they object, and by so many different people? It did occur sometimes that such experiments indicated the presence of an ether wind. Yes, of course, they say, we know that then the apparatus was slightly modified, adjusted and the effect promptly disappeared. It might just be that the error was in the adjusted versions; in them something was done wrong.

But here we have such a fortunate case in which the experiment can be considered verified and the results confirmed not dozens, not hundreds, but even more than thousands of times.

> I regard one experiment more valuable than a thousand opinions created only by the imagination.
>
> *Mikhail LOMONOSOV*

In essence we repeat Michelson's experiment each time we send a light or radio signal to an artificial satellite or to the moon. The time of arrival of the signal depends in no way upon whether the light beam or radio wave is travelling along the motion of the earth or counter to this motion. The beam reflected from the moon spends exactly the same amount of time as on its path to our natural satellite.

Moreover, scientists and engineers, in calculating space routes for artificial satellites and interplanetary systems, pay no attention whatsoever to any ether wind. Nevertheless, their calculations turn out to be correct and the apparatus travels to its required destination.

Here I should like to call attention to the following circumstance. In the 17th, 18th and almost all of the 19th century, the existence of ether was doubted, at least at times, by certain of the greatest theoretical scientists, beginning with Newton. But in the last two decades of the 19th century, as if on purpose, after the death sentence had already been passed on the old ether, it began to receive unprecedented honours from those who did not suspect that these are honours for the dying or are even posthumous ones.

Encyclopedias of various countries, published at the turn of the century unanimously glorified the greatest achievement of physics in the 19th century: the alleged proof of the ether theory, noting with regret that not so long ago some had doubts on this matter. The honest old Brockhouse and Efron Encyclopedia, issued in 1904, 23 years after Michelson's first experiment, contended that the existence of ether had been absolutely and unquestionably proved. The author of the entry in the encyclopedia even expressed his surprise that not long before the famous Lord Kelvin was obliged to give a special explanation to doubting students to the effect that ether really exists.

In the given case, repeating seriously the humorous words of one of the characters in Ilf and Petrov's *Diamonds to Sit On,* we can say that "Brockhouse and Efron were deceiving mankind!"

Only a year after the publication of this volume of the encyclopedia, an entirely unknown patent examiner from the Berne patent office, Albert Einstein, sent a 30-page paper called *On the Electrodynamics of Moving Bodies* to a German scientific journal.

In the theory of relativity, universal space itself serves as the material medium that interacts with gravitational bodies. Space has taken on certain (though far from all) functions previously attributed to ether. Ether was no longer required as a medium providing an absolute frame of reference, because, it now became clear, all systems of reference are relative.

After Maxwell's concept of the field was applied to gravitation as well, the need that Fresnel, Lesage or Lord Kelvin had for ether to make action at a distance impossible disappeared. The gravitation and other physical fields took on the duty of transmitting action. With the advent of the theory of relativity, the field became a primary physical reality, rather than the consequence of some other reality.

The property of elasticity itself, so important for the ether, was found to be associated in all material bodies with the electromagnetic interaction of their particles. In other words, it is not the elasticity of ether that provides the basis of electromagnetism, but electromagnetism serves as the basis for elasticity in general.

Are we to understand then that a universal material medium is no longer required by physics? Are we to return to emptiness: the Void? The situation can perhaps be formulated as follows. Ether was really devised because it was indispensable. At the beginning of the 20th century, the old ether with its attributed contradictory set of properties had lost its necessity. But the very creator of the theory of relativity supposed, judging from certain statements he made, that a certain omnipresent medium did nevertheless exist and had definite properties.

The revolution in science freed such a medium, if it exists, from certain difficult and unreal obligations it had been charged with, and relieved the requirements made to ether by the physicists.

In the twenties of our century, after the publication of his classical works on the special and general theory of relativity, Einstein repeated from time to time in his papers: "...Ether exists. According to the general theory of relativity, space is inconceivable without ether..."; "We cannot manage in theoretical phycics without ether, i.e. a continuum* provided with physical properties."

What does this mean? Is the history of what happened to the void in the 17th century being repeated? Then, upon seeing the Torricellian vacuum, many scientists declared, as you recall, that, nevertheless, a true emptiness is still impossible. And now, after the theory of relativity had made the ether unnecessary, many physicists had no desire to renounce the need for a universal material medium.

Actually, only in outward appearance are these two situations similar. We cannot put an equal sign between the ether that Lord Kelvin wrote about and the ether Einstein spoke of.

"A continuum provided with physical properties" is not at all the previous ether. Einstein has space itself endowed with physical properties. This, for the general theory of relativity, is quite sufficient, no especial material medium besides this is required in this space. But the very space with new (for science) physical properties, could be, following Einstein, called the ether. Moreover, the general theory of relativity is, in the final analysis, the theory of gravitation, no more and no less. In up-to-date physics, "power over world science" is shared by the theory of relativity and quantum field theory. The latter, on its part, leads (more about this further on) to the endowment of vacuum with physical properties. Arkady B. Migdal, member of the USSR Academy of Sciences, writes in this connection, "Physics has, in essence, returned to the concept of ether, but now without its contradictions. The old concept was not taken from the archives; it appeared anew in the development of science".

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* Here, an infinite continuous extent.

Hence, the question arises: why didn't the physicists follow the noble example of Einstein and preserve for this material medium, discovered again in a new fashion, its previous name? The one that was covered with the glory of the Olympian gods and great Greek philosophers, and also the physicists of the 17th, 18th, and 19th centuries. Take the atom; even though it became divisible, it preserved its ancient name. Why didn't the same happen to the ether?

It may be that its role in the different fates of these two terms was played by the circumstance that physicists did not go into the details of atomic structure until sufficient data had been accumulated. The structure of the ether had been discussed with a great many details, thereby "overloading" the content of the conception and making the name less suitable for further use.

Maybe it is just that physics cannot forgive ether because physicists had believed for too long a time in its existence in forms that turned out to be unreal?

Above the Dirac Sea

The founders of quantum mechanics had plenty to deal with in the beginning without worrying about the properties of emptiness. They certainly had their hands full exploring their own unusual new world where energy was divided into definite portions, where a wave turns out to be a particle, and a particle turns out to be a wave.*

But the theory of relativity and quantum mechanics had to meet each other finally and to begin somehow to take into account the discoveries made in each field. This was necessary even if only because elementary particles are capable of travelling at velocities almost that of light at which the mass of a particle begins to depend appreciably on its velocity (as for photons, they travel only at the velocity of light).

The first to begin to consolidate the two theories (a process still far from completion) was the English physicist Paul Adrien Maurice Dirac. Then, in 1928, only three particles were known: the photon, electron and proton. The most "ancient" of these was the electron. Physicists had been acquainted with it for dozens of years. The obvious procedure was to begin with the electron.

Paul Dirac derived an equation that described the motion of electrons on the basis of the laws of both quantum mechanics and the theory of relativity. The result was unlooked-for. The equation for the energy of the electron contained the square root of a certain quantity. Hence, this equation had two solutions: one corresponded, as could be expected, to the well-known electron, a particle with positive mass and positive energy; the other, to a particle with negative energy.

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* The birth of quantum mechanics is narrated in detail by the books: *In Quest of the Quantum* by L. Ponomarev, 1973, and *Probabilities of the Quantum World* by D. Danin, 1983, both published in English by Mir Publishers, Moscow.

Well, so what about it! The simplest conclusion to arrive at is that this solution has nothing to do with physical reality. In any ordinary school problem, in which the x of a quadratic equation (for instance, the number of workmen required to build a house) can have two solutions, positive and negative. The negative solution is naturally discarded because a "minus workman" is obviously incapable of building anything.

But Dirac could not act so simply. He took notice of the fact that obviously, it would seem, unreal particles with negative energy may nevertheless come into being from their positive "antitwins".

Mathematically, everything was clear, but what could such transformations mean in the physical world?

At this point a way out was suggested to Dirac. The Austrian-Swiss physicist, Wolfgang Pauli, investigating how electrons travel in an atom, discovered all of a sudden that these standard particles in each microcell of space differ without fail from one another, either in their energy or their direction of motion. Any possible energy position for the electron in this tiny cell is either free or occupied, and if occupied then only by a single electron.

It turns out that the electrons in the composition of an atom are "selected" as, for instance, boxers in a team, one each in each weight class.

We shall frequently have occasion to return to the Pauli exclusion principle in clearing up the properties of vacuum and, consequently, can postpone a discussion of some consequences following from his discovery. Of importance right now is the paradoxical conclusion Dirac came to when he compared his own results with those of Pauli: all states with negative energy were already occupied by electrons. "All states" is to be understood here literally. Dirac said that this ocean (vacuum) is filled without a limit for the amount of negative energy, and there is therefore nothing resembling a bottom to this electron ocean. The comparison with an ocean (or sea) turned out to be very apt. Vacuum is often called the "Dirac Sea". We do not observe electrons with negative energy precisely because they form a continuous invisible background on which all the world's events take place.

An analogy can be made here. The human eye sees only what moves relative to it. We distinguish the outlines of stationary articles only because the human pupil is itself in continuous motion. But many animals (frogs, for instance), not having such a system of vision, are capable, without moving, of seeing only moving objects.

So we, living in the Dirac Sea, find ourselves with respect to the Sea, with the status of a frog, sitting still on the bank of a pond, waiting for some careless bug to fly by. Without even stirring the frog sees a flying insect, but the pond (in calm weather, of course, without ripples running over the water) is invisible. The role of the bug, for us, is played by particles with positive energy, much rarer compared to the background electrons.

In 1956 Paul Dirac visited Moscow and delivered a lecture called "Electrons and Vacuum". He reminded his audience that it is not so rarely in physics that we encounter objects that really exist but, nevertheless, reveal themselves in no way until occasion occurs. As an example he mentioned an unexcited atom in a state of minimum energy. It does not radiate and, consequently, remains unobserved if not subjected to any action. At the same time, we know for sure that such an atom is by no means something stationary: electrons orbit the nucleus and in the nucleus itself the usual processes, typical of the nucleus, are taking place.

Thus, the fact that the electrons of vacuum are unobservable under ordinary conditions is, in the first place, nothing extraordinary, and secondly does not exclude most complex motions from taking place in the vacuum.

Moreover: of all elementary particles (and not only electrons), without any exception, each has its ocean and these oceans are superimposed on one another. And each one is bottomless.

An entirely enigmatical picture, is it not? How did the physicists manage to think up something so fantastic?

Do you suppose for a moment that the scientists themselves are glad to have obtained what they did? Indeed not! One investigator noted: "It should be clear that even the boldest physicist, endowed with the richest fantasy, would not dare to seriously propose such a conception if he was not obliged to do so by the accumulated experimental data".

Here the "visionaries" often seem to be frightened by the extensive range of their fantasy and, at first, try to justify themselves: I am not glad that it came out as it did, but what could I do about it? That's the way things are. The German physicist Max Born is categorical on this point: "Physicists are not revolutionaries, they are sooner conservative, and only compelling circumstances induce them to sacrifice well-grounded concepts".

Do you think that it is so only in our time, only in the age of ideas which are required forthwith to be fantastic?

Blaise Pascal, who lived in the 17th century, also tried to justify himself after he discovered emptiness in nature: "Still, it is not without regret that I refute these views, so widely held. I do this only to yield to the force of the truth, which compels me to do so. I resisted these new ideas as long as there were any grounds for following the ancient ones". (True, this remark of the famous Frenchman obviously contradicts a statement made by him and quoted earlier in the book, in which he claims that he always contended that nature does not abhor a vacuum.) Maybe Pascal's ideas seemed to be fantastic to his contemporaries as well? In any case, both Born and Pascal complain to an equal degree that truth compelled them to speak frankly....

In any event, the criterion of truth is practice and not the impression that some theoretical construction may make on an untrained mind.

It is quite another matter that some dozens of years after the discoveries of Torricelli and Pascal, anybody could glance at a barometer, which had just then come into wide use, and see for themselves how correct their ideas were. When, however, we are dealing with elementary particles, it would seem that only professional physicists in their laboratories can observe what is happening to the particles. Incidentally, "it would seem" is precisely the expression to use. The principles of quantum mechanics, including the theoretical propositions of Pauli and

Dirac, are at the basis of modern nuclear energy plants. It may well be that you are reading these lines by light that was produced by current delivered from a nuclear power plant.

How could practice confirm the propositions of the theory about the ocean which is, in principle, not observable? But it could. The ocean is unobservable until you treat it in a definite way. When, for example, a quantum of light, rich in energy and called a photon, gets into the "Dirac Sea", the photon (under definite conditions) compels the "Sea" to betray itself, ejecting out of itself one of the innumerable electrons with negative energy. And this should be manifested, contended the theory, in the simultaneous creation of two particles, which can quite readily be revealed in the experiment. One is an electron (an ordinary one with positive energy and negative electric charge) and an antielectron, also with positive energy and with a positive charge besides, for which reason it is entitled to the prefix "anti".

The antielectron was quite soon discovered in an experiment, and by a physicist, Carl David Anderson, who had not then heard about this hypothesis of Dirac. Later the antiproton and certain other antiparticles, following from Dirac's hypothesis, were discovered. Today physicists are quite sure that for each particle in our world an antiparticle can also be found. True, there are cases when a particle, like the photon, which, pluralizing, is its own antiparticle.

All of this, I repeat, is no conjecture; it has been discovered, checked a thousand-fold and then rechecked. The theoretical basis for the discovery was the Dirac multi-ocean vacuum.

> Every fruitful hypothesis initiates an amazingly eruptive flow of unforeseen discoveries.
>
> *Leon BRILLOUIN*

A multitude of conclusions followed from Dirac's theory, including the discovery of the positron and other antiparticles. They gave rise to the concepts of antimatter and even an antiworld. These concepts flourish today, and cosmology has long been engaged in a search for antimatter, as well as an answer to the question of why there evidently seems to be practically no antimatter in our Metagalaxy, and many other allied problems. But this is another story which intersects, from time to time, the history of physical vacuum that we are interested in. Most important for the latter at present is that the properties of physical space, according to Dirac, were determined by vacuum in the form of a universal material background. For the first time the role of vacuum in the universe was based on equations and calculations that could be checked rather than on guesses or even the need for such a medium by science.

"Dirac's Sea" has not dried up in the past half century, only its waters have changed somewhat and its waviness has become in some ways of a different nature. Particles that are unobservable in principle but, nevertheless, interact with ones that lend themselves to observation, have also changed to some extent but, to be sure, only in the conceptions of the scientists.

The "Dirac Sea" has undergone a modification; it has turned into an ocean of physical vacuum.

The other Founding Fathers of quantum mechanics did not agree by far with all of the theoretical constructions of P.A.M. Dirac. But no one could agree or disagree with the fact that a photon having sufficient energy is capable of being transformed into a particle-antiparticle pair.

Facts are stubborn things. The circumstance that this takes place in a vacuum indicated that a vacuum is something complex, and required it to also contain electron-positron pairs before they are revealed by an electromagnetic quantum.

Werner Heisenberg, the famous German physicist, underlined the fundamental significance of Dirac's research on the problem of vacuum. Up to this time it was considered that pure nothing, which, whatever you do to it, whatever transformations you subject it to, is incapable of changing, always remaining the same nothing. Dirac's theory cleared the way to the transformation of vacuum, in which the previous "nothing" turned into a multitude of particle-antiparticle pairs.

Another path, which stemmed from the laws governing any fields known to quantum mechanics, also led to the same conception of particles concealed in vacuum.

An Ocean Beyond the Ocean

What happened next to emptiness in the equations of quantum mechanics?

> We must never forget that each success in our quest for knowledge poses more problems than it solves, and that in this region each newly discovered land enables us to assume the existence of as yet unknown to us unbounded continents.
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> *Louis Victor de BROGLIE*

Back in 1927 Werner Heisenberg formulated the uncertainty relation, a basic principle of quantum mechanics.

It was found that in any quantum physical system the quantities describing it cannot all simultaneously have exact values. The simplest example concerns an ordinary electron, one of the most abundant elementary particles in our world: it is impossible to determine exactly its momentum and simultaneously the point of space it is in. Furthermore, if it is necessary to know its exact position, it can be found, but then you cannot determine its momentum even approximately. You want to determine its momentum? Certainly, but remember that then you cannot find out where your electron with such a momentum is. Of course you can simultaneously find out something about the momentum and coordinates of your electron. But it will be just "something" in both cases. Once you attempt to refine the value of one quantity, you lose even your previous degree of accuracy in determining the other. This has nothing whatsoever to do with the quality of the instruments you employ or the skill of the person conducting the measurements, it is in the very nature of things.

What has all this to do with vacuum? It is certainly directly concerned. Quantum mechanics deals with all particles as quanta of one or another field and does not recognize the possibility of the existence of any portion of space whatsoever where there is no field.

In vacuum there is also this field, only it is one with energy equal to zero, a field without real particles. To be more exact, vacuum is a whole system of fields, not one of which has any real particles (quanta). This is an electromagnetic field without photons (electromagnetic quanta that usually set up such fields), it is a pion field without pi-mesons, an electron-positron field without electrons and positrons.

In a physical system called a vacuum we would seem to be able to simultaneously determine all of its characteristics. Here, at any point, the quantities that might be of interest to a physicist should, it would seem, be equal to zero, and this point can also be exactly located. What a pleasure to have found an exception from the uncertainty relation; at least in a vacuum a quantum system can be determined with all the absolute precision to which we were once trained by the macroscopic world. Nothing of the sort! The laws of nature and the principles established by science know no exceptions. The uncertainty relation positively requires that with a certain probability the energy, for instance that linked with any definite point in a vacuum, must not equal zero.

According to the laws of the same quantum mechanics oscillations are typical of any field. If you have a field, it must oscillate. Such oscillations in a vacuum are frequently called zero-point oscillations precisely because there are no particles there. This leads to an amazing situation: oscillations of a field are impossible without motion of the particles, but in the given case, we have oscillations, but no particles! How can this be explained? Physicists say that in oscillations quanta are created and disappear. These are the same and, nevertheless, not exactly the same, which, by definition, there are none of in vacuum. When an electromagnetic field oscillates, photons are created and disappear. When a pion field oscillates, pi-mesons appear and disappear. When an electron-positron field oscillates, the same happens with electrons and positrons.

This is the same for all kinds of particles corresponding to all kinds of fields known to physics (and incidentally to those which are as yet unknown to physics).

Physics was able to find a compromise between the presence and absence of particles in vacuum (not particles of the Dirac background with negative energy, but ordinary particles with positive energy). The compromise is the following: particles created at zero-point oscillations in a vacuum have a short lifetime, and the heavier they are, the shorter for them is the headlong path they overcome from creation to disappearance.

In all of this, one circumstance should keep us on the lookout. It turns out that particles created from "nothing" and thus acquiring mass and energy, thereby violate the unrelenting laws of conservation of mass and energy. What is this, an exception? Alas, the conservation laws know of no exceptions. Then what is it? The whole point is in the "lifetime" allotted to the particles. It is so short that the "violation" of the laws can only be calculated; it cannot be observed experimentally. It cannot in principle.

Into a microworld I'd enter,
World of unseen magnitudes,
Place where roots of all the causes
And effects put down their roots.
Kingdom of the small dimensions
Where the common moment splits
Into something like a million
Micromomentary bits. *

Vadim SHEFNER

A long time ago, when I was in the ninth grade, I imagined the law of the conservation of matter and the law of the conservation of energy as being two mighty grey-haired old men. Inventors of philosopher's stones and perpetual motion machines of all kinds were fussing around their feet, waiting for the vigilant old men to

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* Translated from the Russian by Alex Miller.

slacken and take a rest for a moment. But laws never take leave.

Later I found that the two old men were replaced in modern physics by a smart and strict young man called the law of conservation of mass and energy. Nothing, it seems, can be concealed from his keen sight. That is why he is the Law.

It turned out that not even these sharp-sighted and alert eyes see everything. The law of conservation of mass and energy, so imperious and omnipresent, refuses to act with full severity during negligibly short periods of time. The sun and the planets with lifetimes of thousands of millions of years, on the one hand, atoms and particles with lifetimes of millionths of a second, on the other hand, obey the law with equal submissiveness. Quite another matter for particles whose lifetime is so short that in each specific case it cannot be noted at all. The conservation law does not condescend to follow their destiny, to see that they obey the laws of behaviour, which are, it would seem, accepted equally in the mega-, macro- and microscopic worlds. One physicist remarked, in this connection, that a particle in the given situation, behaves like a swindling cashier, who regularly manages to return money taken from the cashbox before anybody notices the loss. A particle is created out of "nothing" and disappears on the spot. "On the spot" for such an instantaneous neutron means a lifetime of about 10^{-24} s. An instant electron is lighter, i.e. its mass is less by a factor of two thousand and it can exist two thousand times longer than a neutron, or approximately 10^{-21} s. An ordinary free neutron has a lifetime of several minutes, and when it is part of an atomic nucleus, it can live indefinitely long, as indefinitely long as an electron if you leave it alone. The conservation laws, as you can see, do not for long leave their violaters in peace.

In contrast to ordinary particles, these ephemeral ones are said to be virtual. In this context, they are possible particles. This opens for philosophers a field of application to the concrete picture of a physical vacuum, ancient discussions on just in what the possible differs from the actual, etc.

Nevertheless, the meaning of the name itself should in no way imply that the given particles are possible, since they are called virtual, but actually they do not exist. It should be clear that that which does not exist cannot affect anything, whatever it is. But the possible particles in a vacuum have a quite real effect, as can be observed in precise experiments, on quite real formations of undoubtedly real elementary particles and even on macroscopic bodies.

In what, besides their negligibly short lifetime, do virtual particles differ from their twins in the real world?

These "violaters" of the law of conservation of mass and energy do not have the ordinary relation between energy, momentum and mass. But, to make up for it, all their remaining characteristics are fully respectable. An electron remains an electron in the virtual state as well, a proton remains a proton, etc. They retain their charges and other typical properties with enviable constancy, but only for a very short time, between their creation and disappearance.

The ephemerality of virtual particles leads to a situation in which it is absolutely impossible, according to up-to-date conceptions, to discover such particles experimentally, to register them in some way. They leave no traces in physical instruments.

So what are we to do? Will their existence, following from mathematical calculations, remain a purely paper phenomenon in which you are free to believe or not believe, a phenomenon that may disappear when a change is made in the theory?

Physicists believe that this is not so. Besides mathematics, they have in their arsenal the finest of experimental techniques. Whereas they cannot detect separate virtual particles of vacuum, their total effect on ordinary particles can be registered experimentally.

Let us consider the hydrogen atom. Its nucleus is a single proton about which a single electron travels. (Today the electron on its orbit is no longer conceived of as something like a solid sphere, it is rather more like a cloud smeared at a definite distance from the nucleus along the whole orbit.)

The effect of virtual particles compels the electron to deviate chaotically first to one side and then to the other of the path along which it would travel if there were no virtual particles at all. This phenomenon is called vacuum tremor of the electron. The hydrogen electron is an entirely real particle, faithfully obeying the law of conservation of mass and energy. Hence, the oscillation of the electron on its orbit leads to a change in its potential energy. Such a change can be reliably registered. The phenomenon is called the Lamb shift in honour of the American physicist Willis Eugene Lamb, Jr., who together with his compatriot Robert Retherford first discovered such a shift in 1947.

The magnetic moment of the electron (it characterizes the interaction between a particle and the external magnetic field) also, by its magnitude, bears witness to traces of the effect of vacuum virtual particles. This trace is so clear that the experimentally determined magnetic moment of the electron was previously said to be anomalous, because it differed so greatly from that predicted by theoretical calculations. Now the attribute "anomalous" is purely historical. Today, calculations on the basis of quantum field theory with the effect of the vacuum taken into account yield values that coincide excellently with experimental data.

Here is another example. According to Maxwell's theory, photons should not interact with one another. But experimentally, such interaction, however small, has been observed. Again, it is the virtual particles that are to blame.

It was found possible to observe the effect of vacuum virtual particles, not only in experiments for investigating the interactions of elementary particles, but also in experiments involving macroscopic bodies. Two plates, placed into a vacuum and brought close together, begin to attract each other due to the impacts of the virtual particles. This fact was discovered in 1956 by the Dutch theoretical and experimental physicist Hendrik B. G. Casimir and was called, in his honour, the Casimir effect. The fact is that absolutely all reactions, all interactions between real elementary particles take place with the indispensable participation of a vacuum virtual background, which, in its turn, is also affected by the elementary particles.

It is necessary to point out that according to up-to-date physical concepts, virtual particles appear not only in vacuum. They are also created by ordinary particles. Electrons, for instance, continually emit and immediately absorb virtual photons at such a high rate that the gain in energy during the short lifetime of such a photon cannot, in principle, be observed.

And what is more, any interaction between elementary particles can be dealt with as including the emission and absorption of virtual particles, as an exchange of them.

Furthermore, a real electron attracts virtual positrons and repulses virtual electrons, in accordance with the law we learned in school: electric charges of like kind repel each other, while charges of unlike kind attract each other. As a result the vacuum is polarized because the charges in it are separated in space.

An electron surrounded by a layer of virtual positrons turns out to be behind a real screen of such particles. This reduces the so-called effective charge of the electron manifested in its interactions with other particles.

The polarization of vacuum, as will be evident further on, is a process that should play an exceptionally important role in many physical events.

Each elementary particle, physicists believe today, travels in company with a whole retinue of virtual particles. Dmitri Ivanovich Blokhintsev, associate member of the USSR Academy of Sciences, wrote: "... As a result of the polarization of a vacuum, a charged 'atmosphere' is set up around a charged particle and is linked to this particle".

More often lately, in the Soviet literature, the cloud of virtual particles about a particle is called a coat. A coat can consist of several layers; it pulsates: sometimes appearing, sometimes disappearing and leaving its bearer "bare". Is it possible to disregard such a garment?

Now, when we are dealing with an elementary particle without its indispensable virtual companions, capable of so drastically altering some of its properties, physicists speak of its bare mass and its bare charge, and they admit that the properties are poorly determined. The virtual cortege prevents the distinguished person they are escorting from being properly viewed.

In connection with the problems facing physics, Niels Bohr contended that a person in our time devotes himself to problems that take his breath away and turn his head, but, you feel slightly giddy, you cannot understand their essence. Bohr continued by stating that problems are more important than their solution; solutions may become obsolete, but the problems remain.

Simplicity of the Complex and the Complexity of the Simple

The situation in which a quantum of light, colliding with another particle and giving up energy, creates an electron and a positron can be conceived of in various ways. One possibility is that a quantum of light is transformed into an electron and a positron. Another, according to Dirac, is that a positron is only a hole in a background of electrons with negative energy, that is a hole in place of one of the electrons which was knocked out by the photon.

There is also a third approach. If a particle-antiparticle pair was created from the vacuum, it may be that this pair was not created, not formed and did not appear at the instant we could have tracked it. Actually the particle and antiparticle were in the vacuum beforehand, but in concealed form, and the quantum with its energy just revealed the pair, gave it an observable and, so to speak, legalized status in the world.

All such approaches, it can be said, co-exist in physics on equal grounds. They are descriptions of one and the same phenomenon from different viewpoints and in different words.

We are already accustomed to duality in quantum mechanics. Accustomed so that we are not surprised when in some cases we speak of radio waves and in others about quanta of electromagnetic radiation at radio frequencies, though these are simply two different names for the same things.

This custom of ours is a tribute to the famous principle of complementarity. If you like, you can call it the other side of the uncertainty relation, by virtue of which, in particular, we have become consciously aware of vacuum inhabited by virtual particles.

We cannot find out everything at once about the particle-wave. This makes it necessary to look at it from different angles: in profile, full face, sometimes as a particle, sometimes as a wave.

We came to the microscopic world with the ability to see and to describe what we see, but this ability we acquired during the centuries we spent in investigating the macroscopic world. We brought with us the experience and language of classical physics, its concepts and terminology. In speaking of the coordinates of elementary particles and their momenta, for the properties of microscopic objects we make use of terms that have proved their fitness for macroscopic bodies. They are, however, sometimes not very suitable when we speak of events occurring in the microscopic world.

Many physicists believe that the form itself of quantum theory requires revision that would make it more convenient for describing the microscopic world.

The principle of complementarity, it should be emphasized, is associated, not with the form, but with the very content of quantum theory, and more—with how this world of ours is arranged. This principle, formulated by Bohr, states the following: information obtained in an experiment concerning certain physical quantities which describe a microscopic body is inevitably associated with a loss of information on certain other quantities complementary to the given quantities. Complementary to each other, for example, are the coordinate of a particle and its momentum.

The duality of elementary particles, their nature requires different descriptions complementing, rather than excluding, each other.

At the same time—and quite in the spirit of the principle of complementarity—what has just been said should be complemented with the following. Physicists arrived at the principle of complementarity when they discovered that in experiments involving elementary particles, the investigator himself, with the aid of his own treatment, hinders himself.

We usually find out something about elementary particles from the results of their encounters with other particles acting as probes. In the quantum world such encounters of particles change their properties. The instruments in which we register the particles are by nature always macroscopic objects. The instrument distorts that which it investigates! The event of observation changes what is being observed!

Wolfgang Pauli said that to understand the meaning of complementarity it is necessary to conceive of objects that always begin to move as soon as you look at them with the instrument intended for determining their position. This would, of course, be of no significance if you could calculate the amount of motion and theoretically determine the perturbation due to the measuring operation. But what if this perturbation cannot be kept under control even in principle?

It should be noted here once more that all this is due not only to the instruments you employ. The very nature of microscopic bodies possesses this duality. To observe reality as comprehensively as possible one must complement one description of microscopic bodies with another description.

Must is the proper word; severe necessity compels one. Scientists have no other course in the microscopic world. But is it only there that such a situation prevails? In the last decades, many fields of knowledge, having, it would seem, nothing to do with microscopic bodies, as if envious of the difficulties of microscopic physics, began to adopt, more or less resolutely and successfully, its experience in devising such differing pictures of a single event or object that can complement one another.

As a matter of fact, Bohr himself called for a universal application of his principle. He wrote that the wholeness of living organisms and the characteristics of people having consciousness, as well as human culture, present features of wholeness whose representation requires a typical complementary method of description.

Papers on the principle of complementarity are read at conferences of psychologists, biologists, historians; theoretical works are published which substantiate the application of mutually exclusive "complementary" classes of conceptions of literary history and criticism. Indeed, literature itself has for a long time been demonstrating, in the description of its characters, the application of its own principle of complementarity. The complex world of Shakespeare's characters, the internal contradictions of Dostoevski's—the versatility of their approach to people is readily evident in the works of the greatest writers.

Just imagine how different are the impressions of Julien Sorel of Stendhal's *The Red and the Black* that were had by Matilde de la Mole on the one hand and by her father on the other. Here we have typically complementary descriptions.

Real life was ahead of literature in the application of this principle in the same way that literature was ahead of physics. Since the beginning of time people looked different to different observers, and showed their worth differently in different situations. I would risk contending that the uncommonness of the quantum world compelled physicists to realize a principle that mankind has long encountered.

The universe is enormously complex at the microscopic level, but at all the other levels the world is certainly far from being simple. Not without reason did a physicist recently ask the question: "Are not the successes we enjoy in physics due to its simplicity?"

It is a fact that an acquaintance with the laws of the microscopic world perturbed even the discoverers of these laws. Albert Einstein and Max Planck did not want to agree, at the beginning, with the propositions to which they themselves had been led by the logic of their own theoretical research, not to mention the facts that were discovered by their colleagues.

Discussions, with the participation of these and other most eminent physicists, in which various propositions of quantum mechanics were disputed, have been entered into the annals of science. These arguments perfected the formulations of the laws of the world. It is customary to call this world strange because you cannot simultaneously know both the coordinates of a particle and its momentum, because in it, as Einstein said, "God plays dice with the world", because in it particles have no definite trajectories whatsoever....

"It is often said," notes Victor Frederick Weisskopf, one of the most famous physicists of the 20th century, "that the atomic world is less 'real' than the visible world about us...." He says that we have before us phantasmal formations, obeying laws that seem to be decreed, not by nature, but to be imposed by some crazy king.

With the replacement of the Rutherford atom, reminding one so of the solar system, by an improved model, in which not a solid sphere, but a cloud is smeared along its orbit about the nucleus; with the advent of an atomic nuclear model in which the particles are held together due to exchange with other particles, clarity, it would seem, has disappeared from the microscopic world. But this only seems to be so. Victor Weisskopf calls our attention to the fact that in certain, and even in very many respects, the world that quantum mechanics deals with is far more definite and more clear than our native macroscopic world. In any case, it is built of much more uniform and standard components. Our sun has nine large satellites and hundreds of small ones, but there are no twins among them. Many are the stars in the sky! Many are they in near and distant space! But astronomers would certainly be astounded by the discovery of two absolutely identical stars, even though this is not forbidden in principle by probability theory.

When the astrophysicists really did discover two extraordinarily like quasars, the scientists could not calm down until they found that actually we see in the sky two images of one and the same quasar.

Just try to find two trees indistinguishable from each other, two absolutely identical microorganisms, two cobblestones completely like each other. Any two grains of sand on a beach will be found to differ in some way under a microscope.

But two electrons having the same energy are indistinguishable from each other. The same is true of all the other electrons (with a correction for the energy that each one has). It is true to such an extent that that great master of the physical paradox, John Wheeler once proposed that we assume that all the electrons in the world are one single electron.

It is precisely this super-standard condition of the microscopic world that ensures the stability and unity for the macroscopic world in all its diversity. Victor Weisskopf states: "I like to say it in the following way. Before we got to quantum theory our understanding of nature did not correspond at all to one of the most obvious characters of nature, namely the definite and specific properties of things."

Man has long been able to pick out in the diversity of nature separate, most important aspects, disengaging himself from the rest. When he does this in his mind, we call it abstract thinking. But the extraction of silver from its ore is also specifically such an abstracting operation, only performed in industrial practice. Two ingots of silver are incomparably more alike than the portions of ore they were extracted from. Two atoms of silver cannot at all be distinguished from each other.

The quantum world, the foundation of the macroscopic world, is much more uniform and monotonous than the structure built on it.

Millions of species of living creatures! Millions of chemical compounds! Many thousands of varieties of minerals! Moreover, one quartz crystal can be larger or smaller than a neighbouring crystal of the same kind; they can differ by structural features, bubbles of liquid or gas, fissures, traces of erosion, etc. And last but not least, by simple beauty!

But the silicon atoms that are the components of the crystal, like the atoms of oxygen and those of the other elements all resemble all the other atoms of their kind.

All, absolutely all the chemical elements of Mendeleev's periodic table are made up of combinations of the same three particles: protons, neutrons and electrons (with, of course, the participation of virtual particles, such as, for instance, virtual photons).

But this is already copybook truth. I mention it only to explain why the quantum picture of the universe is not only in some ways more complex, but in many ways simpler than that customary one which we are capable of seeing not only with our mental sight, but simply by looking.

It is more complex because it obeys laws other than those that govern the "upper" part of the physical world.

It is more simple because it is built of a set of standard parts. And each of these parts is built of others, just as standard.

It may well be, however, that we simply cannot distinguish, so to say, the individual features of elementary particles. Vladimir Aleksandrovich Fock, member of the USSR Academy of Sciences, once remarked that we are probably making a not-too-justified assumption when we take all elementary particles of a single kind to be identical to one another. Hence, it may only seem that all electrons are indistinguishable. We are like a bather on a beach that considers all the grains of sand to be identical until he decides to take a microscope with him to the shore (or a handful of sand back with him to a chemical laboratory).

All questions on this matter are very likely to be only rhetorical. So far all data point toward the superstandard nature of the inhabitants of the microscopic world. Those of its riddles that have been solved, and those that are now being solved, even by themselves, without answers to them, demonstrate that the microscopic world is true to the principle: if it is the same kind of particle, it is exactly the same in all of its features.

Today, this goes without saying both in generally accepted theoretical propositions and in the most exotic and eccentric hypotheses.

In the microscopic world only certain events can be called individual ones, i.e. at least partly unpredictable. They are the result of interaction between standard particles (when "statistical probability" begins to operate).

What is, in fact, perhaps the most astounding difference between the laws of the microscopic world and "our" laws (the most amazing, in any case, to my imagination)?

It is not the fact that particles here are simultaneously waves and vice versa.

It proves to be more difficult to become accustomed to another feature of the microscopic world, though it is directly linked with the one just named, and is even a consequence of it. It was found that we can speak of the path of any microparticle, from the photon to the proton, only conditionally. *Physics of the Microscopic World,* a small encyclopedia, sates: "A quantum particle does not travel along a path. . .."

Electrons are passed, one by one, through a narrow slit and strike a photographic film. A tiny spot, almost a point, appears where each electron hits the film. Although the electrons are "standard", and each one in the experiment has the same momentum, the spots appear at different places, and it seems to be impossible to discern any regularity as to where exactly each electron lands. As if a roulette wheel, indicating random numbers, governed the spot distribution. But when many spots have accumulated, a regularity in their distribution is clearly evident. Order is created from chaos.

It is impossible to predict where any particular spot will appear, but the distribution of a great many spots can be predicted.

For this reason, it is said that probability laws are valid here.

Probability theory has long been resorted to by physics, and not only physics, to solve a host of problems. By means of probability techniques we determine, for instance, the velocity of molecules of gas and the mean free path of one molecule of gas before it collides with another such molecule. If, in principle, we knew the exact initial velocity of a molecule, the points at which it collides with other molecules, the velocities of these molecules, etc. we could confidently say what the velocity and direction of the particle of gas that interests us are after any number of collisions.

In quantum mechanics it is impossible in principle to know the path of motion of microparticles; they have no path in the ordinary sense of the word. What then was the kind of simplicity that Weisskopf was speaking about?

In order to find an answer to this question, let us return for a moment to our large and customary world, the macroscopic one. Here, as we know, any path can be calculated, if only because it exists. However, between the possibility in principle and its accomplishment, there is also some difference. Newton solved the "two-body problem"; he found a way to determine the path of two macroscopic formations gravitating towards each other. Since then, the paths of the planets of the solar system, certain comets, etc., were calculated to finest details. But, the "three-body problem" is still unsolved in the general form; this physicomathematical problem proved to be too complex. What is left to say about situations when it is necessary to take into account the mutual influence of a great multitude of heavenly bodies?

As it turns out, our great world is not so very simple....

The quantum world to some extent recompenses the investigators for the impossibility of determining the path of a single particle by enabling them to find out what happens when there are many such particles.

> If we meditate upon the experimental data of modern physics, we readily come to the conclusion that there should always be complementarity in principle between the meditation and the solution.
>
> *Werner HEISENBERG*

If science investigating the macroscopic world is trying on the principle of complementarity, in may be that there are many other enviable principles, laws and hypotheses in the arsenal of quantum physics that are capable of sprouting in "strange" soil.

Vacuum, the main difficulty and the main problem, according to Dirac, of all physics, shows up after each turn in cunning quantum theory, as well as behind the experimental facts and observations in laboratories.

> ...It is a work of science to resolve the visible, merely external movement into the true intrinsic movement....
>
> *Karl MARX*

All the Powers of the World

Two chapters back we mentioned that each real particle exists in the world inside a cloud provided by the vacuum. We also mentioned that when two particles meet, in their interaction, in one way or another their clouds also contact each other (I add that it sometimes happens that a "piece" of cloud is "torn away" and begins an independent life).

Judging from appearances, the role of the vacuum is not restricted to only the supply of material for the cloud. There are many scientists that are searching in the vacuum for the key to the explanation of how and by what laws the principal natural forces act in our world. What are they like, these forces? And how many are there?

A famous ancient-Greek playwright wrote: "And many and mighty are the forces of the world. . . ." But his contemporary philosophers believed there to be very few basic, principal forces in the world. Evidently, they were right. All the forces known to us today amount to only four fundamental ones. Only four and no more.

A stone falls to the earth. The moon rotates about the earth and is held near like on a leash. These are effects of gravitation. It also does not allow the earth to fall apart, the sun and the stars to fly apart and scatter.

But gravitation is too weak to maintain the unity of a stone, a molecule, an atom or an atomic nucleus. The force of gravity, holding worlds in regular motion, is the most feeble of the four forces of interaction known today. The most powerful is the one that is rightfully called the strong force, or rather interaction. (Physicists prefer the word "interaction", especially in the subatomic world, for "force".) The strong interaction holds together protons and neutrons; the strong interaction between two protons is a hundred quintillion quintillion (10^{38}) times as strong as the gravitational interaction between the same protons.

According to conceptions, however, that have been developed in recent years, the attraction between nuclear particles is only an effect of deeper properties of matter. In other words, the sources of strong interaction, the carriers of its supply are the truly elementary particles—quarks.

In that summer month of 1967, in at least one of every three telephone calls to the editorial office, my callers would mention a certain physical experiment. No, they were by far not all physicists. One was a forecaster engaged in predicting the future of science, a biologist that had just returned from a conference on cybernetics, a chemist, etc. It made no difference! The theme concerned them all. And I heard in the receiver:

"It appears that they have been found!"

"Evidently, not...."

"Maybe!"

"It looks like yes...."

"Probably...."

"Nonsense!"

"Maybe yes, maybe no...."

Scientists of all fields are united by the habit of complaining about the fact that the transfer of information between the various fields of science has never been properly arranged. What has been related shows that the situation is not as bad as all that.

The excitement of these scientists, even those in fields far from those concerned with the problem, can be understood. The fate of a theory affecting the very foundations of the world's structure was being decided.

Several years before, some physicists succeeded in discerning order, system, symmetry and, consequently, beauty in the complex world of particles.

The American physicists Murray Gell-Mann and George Zweig showed that this symmetry can be naturally explained under the condition that heavy particles consist of entirely "unnatural" particles with unusual fractional charges, which were named quarks. Why not? Concealed behind beauty should be truth. Physics will never agree with the pessimistic statement of Heinrich Heine:

> Alas! this contest ne'er will ended be,
> The True and the Beautiful will wrangle ever!
> Greeks and Barbarians in wild rivalry
> The ranks of man are always doomed to sever.

But the "barbarous" inclinations of the physicists were displayed in the fact that they began to verify beauty.

There should be an experiment to prove every hypothesis. It was the course of such an experiment that had interested scientists of all fields.

If quarks had been found, it would have been a final confirmation of the latest (at that time) scientific systematization of particles. As a matter of fact, this can best be made clear by a comparison. The discovery of quarks would have been no less significant than the discovery of the nucleus in an atom. It looks very much as if the practical consequences would by no means have been less important (though, let us hope, less dangerous).

The quark has already occupied in the concepts of scientists the place held by the atom at the end of the 19th century, when it also had not been seen, not been discovered, but was only theoretically proposed. Scientists had simply assumed that molecules (these smallest of generally recognized particles ninety years ago) should be composed of some kind of parts.

According to the opinions of a considerable number of physicists, the majority of particles, previously thought to be elementary, are made up of quarks.

Meanwhile, S-F writers abroad were already publishing books about quark bombs.

These particles, as yet theoretical and, consequently, semimythical, were hunted everywhere in the middle and the end of the sixties. They were sought in cosmic rays and in the waters of the oceans, in the depths of our planet and in the atmosphere, in the material of meteorites and on the sun. They are still being looked for.

Each of us, at one time or another, has had occasion to find an acquaintance in a crowd of strangers. Here the case is the other way round. Among "familiar" protons, neutrons, electrons and other known particles we are to find a quark. True, its description is available to physicists. If there is such a thing as a quark, its charge (depending upon the kind a quark) is only 1/3 or 2/3 of the charge of an electron, which, up to the present, was considered to be elementary, i.e. the smallest that exists.

The hypothesis on the existence of free quarks asserts that for each trillion (10^{12}), or perhaps each ten billion (10^{10}) heavy nuclear nucleons (protons and neutrons that make up a nucleus), there ought to be at least one quark. Research conducted by the Soviet physicists V. B. Braginsky, Ya. B. Zeldovich, V. K. Martynov and V. V. Migulin (they hung tiny pieces of graphite in a magnetic field and measured their electric charge) showed that even in a hundred quadrillion (10^{17}) nucleons there is not a single particle with a fractional charge, that is, not a single free quark.

Neither were favourable results obtained by an Italian team headed by Glacomo Morpurgo, which also searched for quarks in a piece of matter hung in a magnetic field.

Other searchers for quarks also had to endure disappointment, after their hopes for imminent success. A team of American physicists led by Robert Adair seemed to be very close to the discovery of quarks in cosmic rays. For six months the counters used by this team registered the arrival of fractional particles. Then, they stopped registering any more such particles and continue their strange behaviour up to the present time.

Even our own sun let down optimistic quarkologists. American physicists found lines in its spectrum that could have been identified with the presence of quarks. But, alas, a more reliable and trustworthy explanation was soon found.

Attempts of a group of American scientists to find fractional charges in the vapours of seawater and many other substances were also unsuccessful.

The dramatic nature of the situation was aggravated by the fact that the theoretical physicists were getting along with quarks much better than their experimenter colleagues. In theory, quarks were holding their own, enabling many previously incomprehensible facts to be explained. Nuclear reactions proceeded as if quarks really existed. The Soviet physicists E. M. Levin and L. L. Frankfurt, as well as some abroad established that collisions of high-energy particles take place in many cases as if not only a particle is colliding with another particle, but as if the quarks of one particle are colliding pairwise with those of the other particle.

Difficulties were encountered, however, by the theoretical physicists as well.

For a long time, for instance, they could not explain what exactly assembles the quarks into elementary particles and holds them in place.

The preceding paragraphs are filled with words expressing disappointment, failure of hopes, "deception" (by the sun) and others.

It really is a pity when you, yourself, have to disprove predictions that you sincerely believe in.

Not to mention the fact that the discovery of quarks would have been written in gold letters in all textbooks down to the ones used in schools, and would remain there for the next thousand years or so. The failure to discover the quark, after being reported in several scientific journals, will be, at best, written up in some university and institute textbooks, in brevier or even finest nonpareil print.

Meanwhile, was the difficulty of the experiment reduced even by an iota only because it yielded a negative result? This depended on nature rather than on the scientists. They did all they were capable of. And, nevertheless, they express their disappointment.

When the physicists and chemists of the 18th century did not find in their experiments any caloric, that they were drastically in need of (it was supposed to be a liquid that carried heat from body to body), maybe they also felt disappointed? The result they obtained was certainly negative (which took the form, incidentally, of the law of conservation of matter).

I am not about to compare the significance of these two negative "discoveries", but do not the situations themselves resemble each other?

But still true remains the old platitude: "He who seeks shall always find." Though, the case with the quarks again seems to prove that you do not always find exactly what you are looking for. But it only "seems to". The scientists of the various countries were seeking, not quarks, but the truth about them. This they found.

Do we gather, then, that there are no quarks? One minute, please. The experiments only showed that in nature there probably are no free quarks that haven't had the opportunity to join in threesomes, forming ordinary elementary particles.

(True, it has been suggested that quarks can exist in the free state as well, but they have such a large mass that they simply cannot be extracted even by up-to-date experimental techniques.)

But it is also very difficult to find free neutrons in ordinary substances. This, however, in no way alters the fact that neutrons are included in the nuclei of all elements (except hydrogen). Moreover it may be that not all the possibilities have been exhausted. Free neutrons are available in nuclear reactions.

In a word, the absence of free quarks has not become the finale of the quark hypothesis of the structure of matter.

Physics of the 20th century is filled with noteworthy battles, and the problem of quarks, it would seem, is only one of many. It seems to me, however, that quarks were sought then, fifteen or twenty years ago, differently than the positron in the already long past, the neutrino relatively recently, or, at the present time, gravity waves. The seekers were more passionate, more emotional, perhaps, even more high-strung. To learn that quarks have been discovered, and then one can die—such expressions could be heard from quite eminent physicists, not famed for an impetuous disposition, that had lived a long fruitful life.

Physicists who were engaged in some other branch of this science talked about quarks a lot more than they should have. Seekers and simply curious scientists were united here, not just by their scientific interests, but by something more.

Just listen to Igor Evgenevich Tamm, late member of the USSR Academy of Sciences: "My greatest desire is to live to the moment when a new system of particles is devised, and to be capable of understanding it". Professor Tamm, as we know, had lived through a long succession of brilliant discoveries, and had participated in some that have changed the very pattern of physical thought. Strange, is it not? If the question concerned simply new knowledge, it is doubtful whether it would have aroused such emotions.

Just what does all this mean? Why is it that quarks, and not some other item from the rich store of predictions made by modern science, have rivetted the thoughts and feelings of physicists?

It looks as if a yearning for simplicity and order is behind the problem of quarks.

From the very beginning, quarks held promise of a return to the good old times of simple physics. Not simple in general, but for them, the physicists. Scientists want to see the pattern of the little bricks of which the world is built. They are convinced that the pattern must be a beautiful one.

> All the essential ideas in science were born in dramatic conflict between reality and our attempts at understanding.
>
> *Albert EINSTEIN*
> *Leopold INFELD*

It had been that way formerly....

According to Aristotle, for instance, there were seven planets, five senses, four elements plus ether. All substances in the world were made of mixtures of particles of these four basic elements. Everything was pretty, convenient and elegant. Then the number of planets turned out to be, if you count the asteroids as well, God only knows how many thousand. Several more dozen senses were discovered, and elements in nature were found to number about ninety. After revealing all this rank disorder, the scientists began to examine what they had discovered, and their aesthetic feelings were outraged. Indeed, they were aesthetic feelings, because scientists more than anybody else are sensitive to the beauty and refinement of their constructions.

"An ungainly equation is faulty" is an ancient mathematical aphorism. All that is complex should be reduced to the simple; diversity to clearcut and unambiguous elements; these, many consider, are the conditions for the success of almost any scientific research.

In the words of the famous Russian chemist Aleksandr Mikhailovich Butlerov: "An infinite diversity of phenomena is to be reduced to a small number of causes." He was not at all contended that the infinite multiplicity of the world reduces to such a substantial number of species of atoms of the chemical elements.

Then the physicists cleared up in outline the structure of the atom, and the chemists could breathe freely. It turned out that there were only two "causes": the electron and the proton, and that all atoms are built of them. Simplicity had been achieved! This idyllic picture of a simple world held out until 1932, when it became clear that the physicists had not solved the problem, but had only shifted it from the shoulders of the chemists to their own. An era began in 1932 in which newer and newer particles were being discovered. The first was the neutron, a neutral particle included in the nucleus. The number of "fundamental principles of the world" now became a trinity. This would seem to be the time to stop, but in this same year the positron was discovered. It is an electron, but has a positive charge instead of a negative one.

Soon the favourite saying of Soviet physicists became: the deeper into the forest, the more brushwood you find. Their favourite tale was about the enchanted mill that kept milling and milling salt without end until the oceans became as salty as they are today. As a matter of fact, physicists did not intend to use only folklore for their jokes. One of them calculated that since 1911 the number of elementary particles has doubled every eleven years, as has the number of physicists. Like any genuine scientist, he linked together these two facts and began to make predictions. Assume, he said, that the number of particles doubles just a little faster than the number of physicists. Assume that one per cent more time is required to double the number of physicists. Then, by the year 15160 A.D. there will be on the earth as many physicists as elementary particles have been discovered by that time. This will enable each physicist to specialize on his own particle.

The physicists were laughing through tears. The more optimistic of them tried to figure out how many particles can be discovered. Murray Gell-Mann (who later became the godfather of the quarks) stopped at the modest amount of several thousand.

But even while the particle numbered tens and hundreds, their classification was necessary all the same. Physicists began to unite them into families on the basis of kindred features. It was not necessary to be a physicist specializing in this line to establish these ties of relationship by examining a table of the elementary particles that lists their properties.

A proton and a neutron, for example, are related, not only by their common residence, the atomic nucleus. The forces in the nucleus binding together a proton and a proton, a proton and a neutron or two neutrons are exactly equal to one another. In mass the neutron is only very slightly heavier than the proton, a wee bit even in the scale of the microscopic world.

Thus, the proton and neutron are twin brothers, of which one is greater than the other in mass and, consequently, according to Einstein's relation, more energetic. The "neutron-proton" pair is called a doublet. A triplet—a kindred threesome—is made up of three pi-mesons: positive, negative and neutral. There are larger families, decuplets, for instance, consisting of ten particles. Also found were particles that have no brothers or sisters, like loners.

The families thus classified looked too small. They included only the obviously close kinships, as if they were really twins. One could surmise that the families should be dealt with as building blocks. A correct arrangement of the blocks with respect to one another should yield a pattern of the world of elementary particles. It was highly necessary to devise a plan of the structure. This was initiated, in the main, by three physicists, who developed the ideas of one another: Murray Gell-Mann of the USA, Y. Ohnuki of Japan and Abdus Salam of Pakistan (it should be noted that the first impetus to this scientific work was given by Ohnuki).

They found new kinships between particles that had no resemblance in outward appearance. Moreover, if we continue to identify families of twins, triplets, etc. (physicists call them charge multiplets) with building blocks, it has been found possible to assemble apartments from these blocks. If one block was missing, if there was a lack of certain parts for a complete apartment, you could determine, from the type of apartment, what the missing block is like. Then the theoretical physicists applied to the experimenters with the proposal: find a particle with such and such theoretically predicted properties.

In 1961 Salam and the Australian physicist John Clive Ward presented the physicists with no more and no less than the prediction that there are nine new particles! In the same year all nine were discovered. Nevertheless, no immediate celebrations followed on this occasion. The new particles did not stand out in any particular way from the many dozens discovered previously. The prediction of the two scientists was too probable an event for it, after happening, to convince world science of something.

You needn't be an astronomer to predict the current sunrise for tomorrow morning. It is entirely a different matter if you can announce a solar eclipse for tomorrow morning.

But Gell-Mann predicted a particle that was astonishingly unlike all the rest. With a negative charge, the omega-minus-hyperon (named so by Gell-Mann) should be 3296 times heavier than the electron; it was the heaviest of all the particles known at that time in physics.

A photograph with a track of the omega-minus-hyperon was obtained first on the Brookhaven synchrophasotron and then on the one in Geneva. This time there was no question of indifference of the physicists to the prediction and the following discovery. The experimenters felt that they were experiencing a historical moment. One of them even mentioned the historical moment when the apple fell to Newton's feet....

Small experiments that we conduct, and our personal efforts ... contribute to the formation of a great river that flows into an infinite sea, though in the name of

> the river there is already no trace of the small streams that supply it.
> What would happen to the Rhine if the small brooks deprived it of their waters?
>
> *Georg Kristoph LICHTENBERG*

One cannot assert that the particles were arranged into a system. But a huge, perhaps decisive, step was made in this direction. The outlines of the system were marked out. To take the next step it remained only (!) to clear up the fundamental reasons why particles are exactly as they are, not otherwise, why they form precisely such families which unite precisely in such a system.

There was a time when the physicists, after discovering protons, neutrons and electrons, explained to the chemists why Mendeleev's periodic system is the way it is, not otherwise. Now the physicists themselves had run up a blind alley. There was nobody to come to their aid. They had to find the way out themselves.

If there are too many elementary particles, the conclusion suggests itself that they cannot be recognized as being elementary. They must consist of some kind of fundamental parts. What kind? This provided a wide range for the imagination. . .and for mathematics.

Gell-Mann conceived, naturally with the aid of mathematics, three superelementary particles. He called them quarks. This term may probably have its origin in Irish folklore. When asked, Gell-Mann, tongue in cheek, speculated on its derivation: "One possible derivation of the name—scholars are already disputing this, some assuming it comes from the German word for rotten cheese—is from a heading of a page in James Joyce's *Finnegans Wake* where Humphrey Chimpden Earwicker rolls over in his sleep to hear a clock strike, and the text says, 'Three quarks for Muster Mark' ".

The "task" assigned to the quarks was to put things into proper order. Theoretically, they coped with it, I repeat, in excellent style, as previously. Incidentally, theories have the property of changing, and theoretical physicists are provident people. Have you any idea why the Gell-Mann quark should have weighed, in the first version of the hypothesis, from seven to ten times more than the proton? Only because if it had weighed less, figured the physicists, it would have been discovered in powerful up-to-date accelerators.

Naturally, the experimenters asked the theoretical physicists: what shall we do if quarks with such a weight are not observed in even more powerful accelerators?

"Then we shall assume," answered one of them, "that the quark is fifteen times heavier than the proton."

This remark was made quite some time ago. Since then the quark hypothesis has changed drastically. Quarks (at least those that compose the proton) have become lighter by a factor of some hundreds. But, in return, the interaction between them acquired, in the conception of physicists, properties that do not allow quarks to become free and exist separately.

> Newton's idea about mutual attraction I consider to be absurd and am amazed that a man like Newton made so many difficult investigations and calculations, having as a basis nothing better than this idea.
>
> *Christiaan HUYGENS*

There is a bewhiskered joke in which somebody asks about the wireless telegraph. He is told to imagine a cat with its tail in Moscow and its muzzle in Paris. When its tail is pulled, it meows. Now that is an ordinary telegraph. A wireless telegraph is the same, but without the cat.

This joke is not out of place here. Elementary particle systematics took shape on the quark basis and it is doubtful whether it will change, even if quarks are never found in the free state. Dmitri V. Shirkov, associate member of the USSR Academy of Sciences, for example, once noted that there is nothing of especial interest in quarks. They are the most ordinary of elementary particles! That is why they managed to be so well predicted. It would have been a great deal more interesting if there were no quarks.

An experiment was conducted in 1980 in an American research institution during the course of which quarks were allegedly discovered. "Allegedly" because there is yet no final confirmation of the discovery, and the conduction of the experiment gives rise to certain doubt. (Because of which I have not mentioned the experiment before.) Nevertheless, no categorical disproofs have appeared since the publication of the experiment. This indicates that there are at least good chances that quarks have really been discovered.

It cannot be stated that the given report was received without interest, that it was not discussed in scientific publications and at symposiums. But all this cannot be compared to the strained attention attracted by similar experiments in the sixties. The reason, evidently, is not only that the physicists had become disappointed by previous setbacks in the search for quarks. And certainly not because, according to some calculations of theoretical physicists, there are no free quarks. An experiment contradicting theory should be even more interesting under such circumstances.

The situation is as follows. The discovery, if it really happened, was overdue. Then, fifteen or twenty years ago, it was impatiently awaited in order to confirm the truth about the new conceptions of the role of quarks. Today these conceptions are already not in need (or almost not in need), according to the opinion of the huge majority of theoretical physicists, of new confirmations. A spoon is of value in time for dinner, as the Russian saying goes. Now, the discovery is, as they say, "redundant evidence" (although, of course, no proof can ever be superfluous).

We have before us, if you please, another paradox, associated with the interrelation between theory and experiments. Only this paradox is of a psychological, rather than of a physical nature.

Nevertheless, there are still insufficient number of quarks to put the elementary particles into complete order, to reduce their numerous throng to a really few simplest particles.

There are already not three, but five quarks. There are many reasons to assume that there should be a sixth. Moreover, each of the quarks can be in several states. Hence, they sometimes speak of eighteen quarks. A bit too many, perhaps, when we recall that in the initial version of the hypothesis, scientists were particularly attracted by the small number (three kinds) of proposed truly elementary particles. By far not the first time in the history of science, the search for simplicity and clarity has led scientists to complexity and diversity.

Strong interaction between quarks is accomplished, like the other three interactions in the world, by the exchange of virtual particles. In the given case, these are virtual gluons (from the word "glue"). There are eight different kinds of gluons. The results of an experiment conducted in 1979 in Hamburg have been interpreted as evidence for the real existence of gluons. The experiment was carried out by a group of physicists from various countries on the nuclear accelerator PETRA (Positron-Electron-Tandem-Ring-Accelerator). Before proceeding it is necessary to point out that though gluons cannot with absolute certainty be considered to have been discovered, there are very few physicists who doubt their existence. Every detail in real reactions proceeds "according to the book", with the "book" based on the up-to-date theory of strong interaction with its quarks and gluons.

Strong interaction between quarks has properties that in no way resemble the properties of gravitational interaction. The latter (like electromagnetic interaction) decreases, weakening as the distance increases. The decrease is proportional to the square of the distance between the gravitating bodies, that is, quite fast. But the mutually strong attraction between quarks seems to increase drastically when they are in danger of being moved away from each other. The more effort we make in an experiment to tear a quark away from its room-mates in an elementary particle, the more vividly it will demonstrate its affection for them. Not by chance have I held forth on the quarks and the strong interaction between them. As you shall see, the very mechanism of this interaction can now be only explained by definite properties of vacuum, and the virtual particles created and disappearing in this vacuum.

The same pertains to the weak interaction, which is so called because it is less powerful by a factor of about ten trillion than strong interaction. It is responsible for only certain reactions between elementary particles. It is no wonder that until the 20th century physicists did not even suspect that such forces exist in the world.

It was not so with electromagnetic interaction, with which mankind has been acquainted for quite a long time. The effects of electromagnetism in the micro- and macroscopic worlds are abundant; associated with them are a great multitude of the most familiar things we have. An atom does not fall apart because the negative electrons are attracted to the positive nucleus; the valence electromagnetic bond between atoms keeps the molecule united. Bodies do not break down into molecules because they are bound, again by electrical forces.

In the majority of molecules the negative and positive charges are nonuniformly distributed. Roughly speaking, two poles can frequently be spotted on a molecule. Neighbouring molecules naturally turn towards one another with their oppositely charged ends. Electrically neutral molecules can also be conceived of as bodies having two poles (dipoles), only these poles continuously change their positions.

But even in such, often apparently random, motions there is an element of order: instantaneous dipoles more frequently turn towards each other with unlike poles than with like ones. This is what explains the mutual attraction of neutral molecules.

Ordinary adhesion of two surfaces is another phenomenon based on electromagnetic interaction. It is sufficient for two of almost any bodies to come into contact for the exchange of electric charges to begin. Free electrons are restless items. There where more of them accumulate, a negative charge appears. Meanwhile, a surface giving up its electrons becomes positively charged. Negative charges are attracted to positive ones, and the surfaces exchanging charges stick to each other or adhere.

The voltage of "adhesive" electricity may be extremely high. It is determined by the force required to tear apart two adhering surfaces from each other. The voltage of such an electric field reaches ten and even a hundred million volts per linear centimetre. However, the energy of the field is very small, all the same, because it is concentrated in a thin layer.

In the same way, specifically owing, in the final analysis, to electromagnetic interaction, a ball bounces when thrown to the ground, an automobile is braked (or even travels), and biochemical reactions take place in the human body. Elasticity and friction, like many others, are only forms taken in our everyday world by profound electromagnetic interaction.

The chemical properties of atoms and molecules are determined by their electron shells. Albert Szent-Györgyi once said that the living cell is, in essence, an electrical machine. The amazing fineness of its biological reactions is due to and can be explained only from the standpoint of quantum mechanics.

Each of us is a system of living cells.

Hence, we shall keep in mind that quantum mechanics is related, not only to the wonders of atomic engineering, it helps us to comprehend, not only the laws acting in the microscopic world, but the forces that control us ourselves.

Gravitation is obeyed by everything there is in the world.

Weak interaction rules over the leptons (this family includes electrons, muons, tau leptons and all kinds of neutrinos).

Electromagnetic force is in charge of all electrically charged particles.

Participating in strong interactions are hadrons, among which the best known are our old friends from the atomic nucleus, the proton and the neutron, plus about three hundred particles already known to physicists; they participate because they are composed of quarks.

Thus, there are four forces, and only one of them, the weakest, gravitation, is universal and omnipresent.

Only four or maybe it is better to say: a whole four? Is it really a lot or too few?

Is it not a brilliant achievement to classify all the almost countless diversity of forces acting in the world on only four shelves, sharply dividing them into four categories?

But the physicists that implemented this achievement are not too inclined to be proud of it. M. A. Markov, Academic-Secretary of the Department of Nuclear Physics of the USSR Academy of Sciences, a scientist whose fruitful ideas have enriched world science to no small extent, said: "Our up-to-date knowledge of the profound properties of matter is, in a definite sense, not far from what the ancient Greeks knew about the world. They supposed that everything in the world consists of four elements: fire, water, air and earth. We consider that all processes in the universe are determined by four types of interaction. These are the same 'four elements' of the ancients".

In one of his papers Markov even tried, extremely arbitrarily, of course, to associate the ancient and modern "elements". He assumed that strong interaction corresponds to "earth", weak to "air", electromagnetic to "water" and gravitation to "fire".

Of chief importance for the scientist, of course, were not the correspondences themselves, but the fact that "we, like the ancient Greeks, do not yet understand the relations between our four elements".

A huge majority of physicists are very sure that these relations exist, that they are acting and that it "only" remains to find and understand them.

Up to Faraday, that is only some hundred and fifty years ago, physics sharply distinguished electrical and magnetic phenomena from each other (there being, of course, no question yet of relating these or others with such things as elasticity and adhesion). Now physics has joined the two in a united electromagnetism.

M. A. Markov insists: "Shouldn't our four kinds of interaction be united together in the future in the same way? I'd so much like to ask, if there was somebody to ask: Dear Lord, whatever dost Thou need four kinds for?"

Meanwhile as they say, the world is built without architectural excesses: no one of the kinds of interaction can be completely described separately from the others. This is extra confirmation of how firmly all is bound together in nature, including the forces that govern it.

Very recently three physicists became Nobel Prize Winners for taking the first steps in the construction of a consistent theory uniting weak and electromagnetic interactions. Their premises and conclusions are being checked, refined and further developed. Meanwhile, work is proceeding on the uniting of three interactions simultaneously: electromagnetic, weak and strong. Only gravitation that Markov associated with ancient "fire" remains, for the time being, somewhat outside this energetic research. But its turn will certainly come. And is already coming.

To provide the theoretical physicists with a bridgehead on which they could unite all or almost all the forces in the world, the idea, to whose adventures this book is devoted, must undergo changes. It is already undergoing them. In emptiness, which ceases to be simple emptiness, scientists are discovering—or at least are assuming—newer and newer properties, without which each elementary particle, any item and the metagalaxy itself, as a whole, would be different.

We can make the following statements: (a) the properties of vacuum determine to a great extent the nature of interaction between particles and bodies; (b) the nature of the interaction between particles and bodies determines to a great extent the properties of a physical vacuum.

Both statements are true. Because the interaction of particles with a vacuum is what specifies the laws that govern world forces.

The current unifiers of these forces try to make out in them a certain common unified force, a unified universal interaction of nature.

The Soviet physicists D. A. Kirzhnits and A. D. Linde write: "The dynamic foundation of interaction—strong, weak and electromagnetic—constitutes a unified fundamental law.... This law, which can be identified with the simplest law of electromagnetic interaction, would be effective in its pure form only in the case when there are only interacting charges." That is, not in our physical vacuum, but only in the ancient absolute emptiness (which, as a matter of fact—Aristotle, Giordano Bruno and René

Descartes being correct—is impossible) all three interactions would be long-ranged and the forces, binding particles, would decrease proportional to the square of the distance between them.

There is no absolute emptiness in our real world and, consequently, nowhere for the "unified fundamental law" to manifest itself in the pure form! It is therefore necessary to judge such a law by the effect of other laws that follow from it.

Here scientists begin a sort of game. A good model of such a game is the solution of a multiple-move chess problem. The pieces are arranged on the board. It is known which side succeeds in checkmating the other, and even in how many moves. Moreover, we also know that according to the rules adopted by chess-problem composers, the solution of the problem cannot, in particular, begin with a "forceful" move, that is, by checking the Black king or capturing a piece, even if it is a pawn.

The board and pieces in physics are the known facts; laws previously established by science are the rules of the World Chess Federation. Even the principles used in composing chess problems have a suitable analogy: almost in any field of knowledge scientists call an assumption or supposition "forced" when it is weakly supported. They evidently call it that because it is imposed on them by nature, so to speak, by force. This, however, is an inadequate and, as a rule, worthless procedure.

In a good chess problem the composer will certainly provide false tracks for decoying the solver along the wrong way. Nature has an abundance of such devices; they are, as Einstein once said, highly refined ones, but its problems do not change in the course of their solution like the chess problems. It is quite another matter that they sometimes begin to look different to us. This means that a misprint has slipped into the collection of problems. Neither the chess-problem composer nor nature is to blame, only the publisher, that is, the scientists who incorrectly stated the conditions.

Of assistance in solving a chess problem is a knowledge of the theory of their composition plus experience in solving such problems accumulated by the chess player and that imparted to him by his teachers.

There is one more important resemblance between our tentative model and what it is simulating: in a proper problem there is not a single superfluous piece, Black or White, unnecessary for the solution. Here, as in nature, all is interrelated. The solution of a proper problem ends with a proper mate.

An old *Chess Player's Dictionary,* published in Russian, states the following: "A proper mate, or mate pattern, is one that is simultaneously pure (i.e. all squares in the vicinity of the mated Black king are occupied by its pieces, without being threatened by White pieces, or having been attacked by White pieces only one time) and economical (i.e. all the White pieces participate in the mate position, with an exception being allowed for the king and pawns)."

Well, in a proper solution of some scientific problem, absolutely all the "pieces" that are involved in one way or another in the problem, must be taken into account.

It is true, however, that in the course of time, as we know more and more about our world, the "pieces" themselves—known particles—change, as do their properties—the "moves". But in chess as well, during its long history, its rules have changed. There was a time when the queen moved in the same way as the king: only one square in any direction. It was only in the 19th century that the rule was finally revoked that rewarded a journey of a king to the opposite side of the board, across all the parallels of squares, by adding a new pawn (a true analogue of matter being created "out of nothing").

The very approach to chess has changed. In the words of Grand Master S. G. Tartakover, the impression made in the twenties on the older generation of chess players by the system of chess playing, associated with the names of A. Alekhin, A. Nimzovitch and R. Réti, follows: "Plans that would never occur to us, openings that leave a morbid imprint on the whole game, moves disregarding free development of the pieces and, finally, methods consisting of a continuous crafty accumulation of concealed pressures."

This recalls the remark, amazingly similar in essence, made by the physicist Max Planck: "In place of clear and lucid images. . .a striving appears towards some kind of mysterious schemes that are not subject to clear-cut conceptions."

Hence the indignation of certain advocates of classical physics upon the advent of quantum mechanics had, as you can see, its analogy in the world of chess theory.

(I remind you, however, without delay, that in chess as in physics the views of the "newest school" were confirmed by practice, i.e. games that were won.)

Next, scientists, solving a physical problem of nature, begin to review various feasible versions, to seek what moves lead to its solution. Here we can recall an old formulation: each well-posed problem already, in itself, contains its answer. Problems posed by nature always have answers; it is of importance "only" to properly arrange the pieces on the board. In physics, of course, they are far from being always known.

D. I. Blokhintsev, late associate member of the USSR Academy of Sciences, once made an astounding statement: "From a purely professional point of view as a theoretical physicist and philosopher, I should consider that there are always sufficient facts, and that there is not enough imagination."

Just what does he mean by "always"? The first impulse is to regard this bold assertion as not very serious and to dispute it. But then we involuntarily recall that experimental proof (a fact) that there is no ether (the Michelson-Morley experiment) existed almost a quarter of a century before Einstein acquired sufficient imagination to do without this same ether in his picture of the world.

Thus, it may be really true that modern physicists solving the problem of unified interaction also have sufficient facts, and the solution depends only on the imagination, that is, on a fruitful idea.

There is no emptiness, but there is a material medium, the physical vacuum. This means that it should, or at least could be blamed for changing the nature of interaction, making weak interaction short-ranged, and electromagnetic and gravitational interaction long-ranged. It is this vacuum that treats different forces in an entirely different way, and this prejudiced attitude hinders us in clearing up the essence of the problem.

A simple analogy, though not very close, can be demonstrated. A piece of wood floats in a pond, a piece of metal sinks. Cannot this be interpreted as different treatment afforded by the material medium (water) to different substances? Here the behaviour of the pieces depends upon whether their specific gravity is greater or less than that of water.

Do you remember the remark about the world being built without architectural excesses? Physicists also employ another comparison from architecture and construction terminology. A favourite remark of the Soviet scientist D. A. Kirzhnits, Dr. of Physical and Mathematical Sciences, is that our world turns out to be built, in general, according to the type-design principle, and if not of type-design elements, then at least according to type designs that closely resemble one another. The same phenomena play a fundamentally important and similar role at various levels in the structure of matter.

It may probably prove possible to put electromagnetic and weak interactions on a common basis if, with respect to the former, vacuum will be a dielectric, and, to the latter, it will be a conductor. The first of these conditions, as is known, is met by nature. Unlike charges in a vacuum exist for an indefinitely long time without mutually annihilating one another. An electrodynamic vacuum does not pass an electric current; it is a nonconducting medium, a dielectric. What kind of properties can a vacuum have so as to prevent weak forces from escaping from the very narrow limits of action typical for them? What in vacuum is capable of transforming initially unified universal interaction into its weak form, which differs, primarily from its electromagnetic aspect by its action at an extremely short distance.

D. A. Kirzhnits is the head and A. D. Linde is a member of a group working on the theory of superconductivity at the Lebedev Physical Institute of the USSR Academy of Sciences. This may be why, in regarding a vacuum, they compare the phenomena possible in it with those that are typical for metals and alloys in a state of superconductivity.

Superconductivity is a property of electric conductors to pass a current, under certain conditions, without any resistance whatsoever. How can we here, it would seem, speak of superconductivity in vacuum when, as just mentioned, it is not a conductor at all? Even if superconductivity is feasible in a vacuum with respect to currents corresponding to the weak interaction, how can the capacity to conduct current without resistance restrict the action of any possible kinds of forces?

Physicists have the following to say on this matter.

Nature imparts superconductivity to substances that have an ordered structure of a special kind. Electrons, which in an ordinary conductor you could say "pay no attention to one another", are found to be interrelated in a superconductor. They depend upon one another, travel in the form of pairs, and these pairs continually, as in many old dances, for instance a square dance, exchange partners (i.e. electrons). In other words, the pairs keep disappearing and reappearing in other versions.

We obtain a genuine collective, or company, of electrons. The small Russian encyclopedic handbook *Physics of the Microscopic World* states: "All the electrons in the system are bound to one another, and one electron needs to be "broken away", or detached, not from a separate pair, but from the whole system of interacting pairs of electrons. This obviously is much more difficult to do...."

In a superconductor, as long as it retains this state, there are no forces capable of detaching an electron from the "dancing company". This is manifested as the lack of resistance to electric current.

Electron pairs are by no means the only ones capable of gathering together into collectives of interrelated particles. All elementary particles, as well as groups of bound particles, capable of demonstrating such collectivism, are called bosons in quantum physics, and such collectives are called Bose condensates. (Somewhat further on we shall discuss in detail what bosons are. Here I add only that they were named after the Indian physicist Satyendra Nath Bose.)

Owing to the Bose condensate, current passes through a superconductor without resistance, but there are factors that a superconductor can resist with an astounding effect. If you place it into a magnetic field, the field (i.e. the photons that make up the field) is unable to penetrate into the depth of the superconductor. The superconductor "defends" itself, repulses the field, does not let it in. Why? It is the field itself that sets up a line of defence against itself; it induces in the superconductor induction currents, which, as could be expected, are not damped since they encounter no resistance. The induction currents repulse the field that induces them (this phenomenon is called the Meissner effect after Walther Meissner, the German physicist who discovered it).

The magnitude of the force exerted on a conductor, which carries a current and is placed in a magnetic field, is determined by Ampère's law. The intensity (or strength) of a magnetic field set up by an electric current is determined by the Biot-Savart-Laplace law. In principle, the action of both of these laws is not restricted by distance.

The whole discussion on superconductivity was required in order to state: owing to the Meissner effect, Ampère's law and the Biot-Savart-Laplace law become, when dealing with a superconductor, laws with short-range action. With short-range action like weak interaction. In this manner, we have bridged the gap between superconductivity in a metal and the properties of vacuum. This also seems to be the answer to the second question at the beginning of this very long discussion on superconductors.

Virtual particles in vacuum (more exactly, certain kinds of virtual particles) are not in a state of chaotic disorder. With all their ephemerality of existence in time, they form an ordered system, that is, a field in vacuum has an "organized" structure. Kirzhnits and Linde succeeded in showing that this order is related to the one typical for a field in a metal that is in a state of superconductivity.

The system of equations describing superconductivity in a metal is practically identical to the system of equations characterizing a vacuum.

Real electrical currents are not damped in a superconductor. In a vacuum these currents correspond to the undamped motion of virtual particles encountering no resistance, including those that carry no electromagnetic charge. The particles are what forms the screening around the sources of weak interaction which restricts its range and makes the interaction itself short-ranged.

In absolute emptiness nothing like this would occur. There, weak interaction would be long-ranged, along with electromagnetic interaction. From this, striking conclusions follow. It is known that in the electromagnetic interaction of charged particles, an exchange of virtual photons—the quanta of electromagnetic energy—occurs between the charged particles. Weak interaction consists in the exchange of other intermediate particles. They were called weak (intermediate) bosons. In contrast to real photons, weak bosons could not be discovered in experiments for a long time. As assumed, such bosons should have had a rest mass that photons do not have. Moreover, this mass should be eighty to one hundred times greater than that of the proton. (The interaction is, of course, carried out by virtual bosons, whereas the discovery was to involve the corresponding real particles. At the beginning of 1983 some foreign journals reported that such a discovery had been made.)

Weak interaction could not become long-ranged in absolute emptiness if weak (intermediate) bosons had no rest mass in such emptiness. It follows that such particles owe their mass to the material medium called "nothing", that is, vacuum. Bosons acquire mass only in vacuum, in a collective of virtual particles: the Bose condensate.

In the final analysis, all of the above demonstrates the role of vacuum in the theory unifying weak and electromagnetic interactions. Not so long ago the Nobel Prize was awarded to Steven Weinberg, Abdus Salam and Sheldon Lee Glashow for developing this theory. In the above we dealt with one of the aspects of the theory in whose investigation a notable role was played by Soviet physicists.

Now let us look, at least from a distance, at how the special properties of vacuum are resorted to to draw the unified (according to the Weinberg-Salam theory) electroweak interaction nearer to another, the strong interaction.

What kind of a force binds the quark and antiquark in the nucleon so that they cannot, possibly in principle, be torn away from each other? What is this force which, notwithstanding all that is typical of the other interactions, increases as the quarks are withdrawn from one another, thereby not allowing the system to be disrupted? And how, finally, can such a force be an effect of the same unified universal interaction?

Many scientists are working on the following possibility. Vacuum, according to their assumptions, is capable of expelling from itself a strong field, like it expels a weak field. Here the field between the quark and antiquark is compressed into a tube which is called a string. According to calculations, the energy of the string should increase with its length. Thus, in an attempt to draw apart the quark and antiquark, the string will operate as a spring resisting tension.

Several specific mechanisms have already been proposed for the origin of the force that causes the formation of a string between the quarks. One of such mechanisms again includes the conception of the Bose condensate and the ordered structure of a field in vacuum. This time such a collective is to be formed by virtual gluons (gluons, I repeat to be on the safe side, are intermediate particles in interaction between quarks, like photons between particles with electromagnetic charges).

There is also another version of the explanation of why the bonds are so strong between quarks. Let us recall what happens to an ordinary electron in vacuum. The electron redistributes the virtual particles, and orients the electron-positron pairs in a new way. The virtual positrons surround the electron, screening its charge.

A real quark in vacuum also encounters virtual "quark-antiquark" pairs. But while the virtual antielectron (a positron) is attracted to a real electron and a virtual electron is repulsed by a real electron, both quarks and antiquarks can, according to the laws of strong interaction, only attract each other. Hence real quarks turn out to be compressed, gathered in inseparable unity by direct pressure of their virtual fellow particles.

This picture can also be described in another way. Two real quarks turn out to be as if enclosed in a cavity that drastically differs in its properties from the vacuum surrounding the cavity. The cavity is a bag or catcher. In vacuum, ordinary oscillations are damped, or inhibited, within the bag, whereas outside they take place as usual. The pressure of the virtual particles hold their real fellow particles in the catcher.

We can even speak here of the surface tension at the boundary between the cavity, inside of which the vacuum is changed by the quarks, and the vacuum surroundings of the bag. This is, of course, only an analogy. The words "surface tension" constitute a physical image taken from a scientific field that has no relation to vacuum. There is a possibility of employing, not only terms, but concepts and notions from neighbouring and even distant fields, from a store used by scientists working on different floors of the universe. This very possibility demonstrates the unity of the world, the "love nature has" for type design and standard components.

The aforegoing is still only a hypothesis, one of many hypotheses, by which physics ascends in steps to the unified theory of interactions. It is worthwhile to note that hypotheses endeavouring to unite electromagnetic, weak and strong interactions are spoken of as theories of the Grand Unification.

It appears that such a unification of world forces deserves the name "Grand". But to the three forces, in order to obtain a genuine unified field theory, we must add gravitation. The continuing complication of emptiness has led to a situation in which scientists begin to discuss gravitation as a manifestation of certain properties of vacuum and to seek its origin specifically in these properties.

According to certain suppositions, real particles acquire their very mass owing to a special kind of those particles, cheated by fate, that are patronizingly called feasible, or virtual.

The hypothesis concerning the existence of such particles that impart mass to other particles and the corresponding field was proposed by the Scottish physicist Peter Ware Higgs and is called by his name. Higgs' real particles should have a huge mass and therefore we are still far from obtaining them by means of an accelerator.

Under present conditions, virtual particles of any kind are present throughout vacuum. While interaction between particles by means of virtual photons is manifested in the form of electrical charges, the interaction of ordinary particles with Higgs' virtual particles is displayed as the possession of mass.

Gravitation, according to certain hypotheses, can be explained by special features in the behaviour of virtual particles. This may be their polarization, which resembles the polarization of an electron-positron vacuum that was mentioned previously.

Discussing (in a paper published in 1981) the feasibility of such an approach to gravitation, Ya. B. Zeldovich, gives the comparison: "The first half of the general theory of relativity consists of a discussion of the motion of particles in a curved space-time. The curvature influences the motion of the particles.... According to Newton's third law—an action is always opposed by an equal reaction—it is natural to conceive that there is a reverse effect of the particles and fields on space. When the tracks exert a force on a railway car, turning its path, the car exerts a definite force on the track rails. The second part of general relativity is similar to a discussion of the behaviour of the rails. Besides the force exerted by the railway car, you must take into account the elasticity of the rails and their connection to the ties and the embankment. One can say that Einstein's equations describe the elasticity of space...maybe this elasticity is completely determined by the effects of vacuum polarization, i.e. is similar to the Kasemir effect."

Dr. Zeldovich did not, of course, employ the word "maybe" by chance. Hypotheses remain hypotheses until they are confirmed.

It is difficult to predict what specific versions will turn out to be valid. Even the foundation of the Weinberg-Salam theory, the one most widely recognized today and that unifies only two interactions, may be subject to strong attacks from opponents. In any case, this theory will certainly be altered in some manner.

There is only one thing, perhaps, that can be vouched for: any unified field theory should be closely related to the properties of physical vacuum; its conclusions should be based on these properties and, at the same time, clear them up.

> **No matter how great the difficulties entailed in the discovery of new truths in investigating nature, even greater difficulties stand on the way to their recognition. These difficulties depend on various causes and are, in essence, sooner helpful than harmful for the general state of science...it is better if truth, once it is understood, be doomed to a long struggle, than to have everything that is created by the fervid imagination of man gullibly welcomed.**
>
> ***Jean Baptiste Pierre Antoine de Monet, Chevalier de LAMARCK***

Variable Vacuum

Since vacuum is actually in no way an emptiness, or void, neither is it a chaos, nor some orderless jumble of virtual particles, but, instead, a genuine and orderly system, we can ask: does it always retain these properties? Everybody knows that order in this world, like in any ordinary apartment, is much easier to disturb than to maintain.

Our ordinary superconductors—metals and alloys—lose their superconducting properties with exceptional ease. It is sufficient to place them into a magnetic field which is strong enough to breach the line of defense that they themselves had built. An even simpler way is to raise the temperature of the metal above the critical point. This entails no difficulties whatsoever. Indeed, it is the reason why we cannot obtain or even maintain the state of superconductivity at any high temperatures. Incidentally, the word "high" is an obvious overstatement, notwithstanding the stipulation "any". In a compound of niobium and germanium, one of the record breakers in the field of superconductivity, it appears only at 23 kelvins (23 °C above absolute zero). This, today, is a record "high". A Bose condensate of electron pairs cannot endure even at tiny bit higher temperature. The electrons part company, and now not to form new pairs, but to remain, so to speak, in eternal solitude. In place of bosons that enjoy the company of their ilk, we again have ingrained individualists. *

To initiate such a "general divorce" we need only, I repeat, to raise the temperature to 23 kelvins, i.e. to a point from which there is still two hundred and fifty degrees up to zero degrees of the Celsius (Centigrade) scale.

In exactly the same manner, a magnetic material, when heated to a definite temperature (a much higher one, of course) loses its magnetic properties. This occurs because the ordered structure, which provides for these properties, disappears.

Heating is, in general, a rabid enemy of order. Sooner or later, it transforms the elegant and clear-cut structure of a crystal, first to a less ordered system of weakly bound molecules of a liquid and, finally, to a gas, whose name was deliberately derived from the Greek word "chaos".

The Bose condensate of a vacuum is much more stable against heating than the structure of a magnet or a crystal. A Bose condensate of virtual particles does not fall apart even at the temperature of six thousand degrees Celsius that prevails at the sun's surface. It can even withstand the temperatures in the interior of the sun, that is, millions of degrees.

Vacuum, according to the Weinberg-Salam theory and to the investigations of Kirzhnits and Linde, loses its superconducting properties only when the temperature is raised to 10^{15} or 10^{16} degrees. This figure is, of course, a fantastic one. Even the outburst of a nova occurs at a

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* The reader understands, of course, that all this anthropomorphism in application to the microscopic world, or in general to inanimate nature, is no more here than a literary device.

temperature of 10^{11} kelvins (a hundred thousand million degrees).

The hope exists, nevertheless, of checking this still purely theoretical conclusion by means of observations. Certain particles, included in the composition of cosmic rays, carry tremendous amounts of energy. Upon collisions with matter this energy may, roughly speaking, be evolved as heat. The temperature of the vacuum in the vicinity of such a collision is capable of exceeding the critical value named above. Then the vacuum, even for a negligible fraction of a second and in a negligible volume, can have its properties fundamentally changed.

What is supposed to happen to the weak and electromagnetic interactions in the "new vacuum", which has lost its superconductive properties with respect to the first of these interactions?

Since there are no more undamped currents of virtual particles about the weak charges, no screening is induced that limits weak interaction in space. Escaping from strict wardship, this interaction turns into the long-range type, as it would be, as we now know, in absolute emptiness. Meanwhile, the carriers of long-range forces can only be particles which, like the photon, are deprived of rest mass. Correspondingly, the intermediate bosons, carriers of weak interaction, should also lose their rest mass. But, to make up for it, the neutrino in this situation acquires the capacity to interact with matter more strongly than the electron does. After this, the neutrino can nowise be called "elusive" and a "ghost particle".

According to the theories of the Grand Unification, a certain variety of Bose condensate is conserved in a vacuum at a temperature of even 10^{16} degrees. This remaining Bose condensate provides for the difference between strong interaction and the unified electroweak interaction.

A temperature jump up to 10^{27} degrees (up to a million sextillion degrees) is required for this last ordered system to disappear.

In this "supernew", absolutely chaotic vacuum, not only intermediate bosons, but almost all the rest of the particles will lose their rest mass. A frenzied succession of their mutual transformations will begin; boundaries will vanish between the classes of particles that under ordinary conditions have a minimum of features in common. A quark, for example, will be able to freely turn into an electron and vice versa.... In a word, together with the change in the structure of vacuum, almost all things will change in our world....

The proposition that the properties of a vacuum can drastically change has relatively recently been substantiated by D. A. Kirzhnits and A. D. Linde. A series of studies devoted to the theory of phase transitions in a vacuum won these Soviet scientists the Lomonosov Prize of the USSR Academy of Sciences.

Verbs in the above description of the "supernew" vacuum are all in the future tense, whereas the past tense would be more accurate. Physicists and astrophysicists relate such a state of vacuum and the corresponding state of all matter in the metagalaxy not with the future, but with the very distant past, in fact, back to the first instants of life of our metagalaxy. Incidentally, can we speak here of instants? It has been measured that a "twinkle of an eye" takes about one-tenth of a second. Here we are dealing with lengths of time less than a second by a factor of many quadrillion quintillions. The separation of the strong and electroweak interactions should have occurred, according to theories describing the Big Bang and subsequent expansion of our universe, when this expanding universe had already cooled to a temperature of 10^{27} degrees. Such a temperature was reached in no longer than 10^{-35} second after the beginning of the Big Bang. It was at this instant that a rest mass was acquired by quarks and electrons, muons and many other particles that had, until then (so briefly), managed without one.

The transition of the universe to a new phase state thus occurred.

Next we give the floor to Kirzhnits and Linde: "It is of interest to note that in some versions of the Big Bang theory almost all the energy was concentrated, preceding the phase transition, in the vacuum...and only a negligible part was shared by the matter itself. Following the transition, excess energy of the vacuum was transformed into energy of matter, which appeared during the phase transition in the form of 'particle-antiparticle' pairs and quanta of radiation*. Hence, an observer would find at the instant of the phase transition the creation of practically all of the energy of matter: essentially 'out of nothing'. It stands to reason that actually no creation of energy takes place and the energy is simply transferred from the vacuum to the matter. Nevertheless, this fact is in itself quite extraordinary, being an effect of the existence of Bose condensate, which is capable of storing and releasing energy."

The second phase transition, at which the weak and electromagnetic interactions became different, occurred not very long after the first transition. The universe had time to cool to a temperature of ten quadrillion (10^{16}) degrees at the instant following the beginning of the Big Bang by 10^{-10} second.

This time, among all the particles that existed then (as well as those existing up to the present time), only the photon and, possibly, the neutrino remain deprived of rest mass. All the other particles have acquired one.

Then the temperature dropped by a factor of ten thousand, to 10^{12} kelvins, and the free quarks united into nucleons and mesons (and were held in such unions, as we already know, by ordering acquired by the vacuum). This led to the very possibility for the formation of atomic nuclei, which are built up of nucleons.

Each "drop in the mercury column" of the thermometer applied to the world brings us nearer to today's standard, to our ordinary picture of the universe, a picture whose bright-coloured paints have been applied to the "primed canvas" of vacuum.

Thus are pictured the events that occurred in the first fraction of an instant after the creation of our metagalaxy, in the light, of course, of up-to-date concepts of the Big Bang, which started off the only part of the universe known to us.

It is worthwhile to add that it is specifically the new-

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* The energy embodied the virtual "spectres" in flesh.

est theoretical investigations concerning the structure of vacuum that have provided the basis for the proposition that the Big Bang, twenty thousand million years ago, could occur not exactly in the form that the majority of physicists had until recently agreed upon. It is customary to assume that at the instant before the Big Bang all the matter in the metagalaxy was in a special state of singularity, that is, in the roughest approximation, it had infinite density.

Certain features, which characterize the polarization of vacuum, seemingly enable us to manage without any singularity, to "make" the transition of our universe that occurred 20 thousand million years ago from compression to expansion a smooth one. They enable us to begin to count off the existence of our metagalaxy, not from zero, but rather from "minus infinity". The aforesaid is from papers on the subject published in recent years, among others, by the Soviet scientists Ya. B. Zeldovich, L. P. Pitaevsky, V. Ts. Gurovich and A. A. Starobinsky. This solution by no means cancels the tremendous research carried out by theoretical physicists investigating the first instants of the expanding universe, but, instead, makes certain corrections.

It is clear why many physicists find this hypothesis attractive. The general theory of relativity, and all of up-to-date mathematical physics, is incapable of carrying out calculations that can deal with extremely complex situations involving an exceptionally high density of matter. With this hypothesis they can manage to get rid of a singularity with such a density.

Finally, it is necessary to add that a point of view exists (in the research of M. E. Gertsenshtein and M. Yu. Konstantinov) according to which, during the transition of the metagalaxy from compression to expansion, the quantum effects associated with vacuum are manifested in a much less degree than in the hypothetical versions of the development of the universe mentioned previously.

Laws and Forbiddances

> It may seem audacious that we, limited as we are for making observations within the space of our small earth, a speck of dust in the Milky Way and limited in time to brief human history, venture to apply laws, discovered for this confined region, to the whole immeasurable, boundless space and time.
>
> *Hermann Ludwig Ferdinand von HELMHOLTZ*

This statement was made in the 19th century. Today, the universe has, for us, become wider and deeper. As before we dare, not only to make discoveries in it, but to impose on it laws discovered on the earth and its immediate vicinity. What is most astounding is that nature continually confirms our right to such audacity on the scale of the universe. On the infinitely distant stars, between galaxies beside which our whole solar system is but a speck of dust, rule the same laws of Newton, Einstein, Maxwell and even Archimedes. This leads to the conclusion that laws which we do not yet know and theorems that have not yet been formulated also have the same universal power.

Why?

One answer is that in the whole diverse universe, vacuum is the same. The laws of the world are prescribed specifically by the properties of vacuum. Among them are those that physicists define by the capacious term "symmetries of vacuum".

The laws of conservation of mass and energy are only the more prominent representatives of the imperious family of conservation principles that rule our world within the scales of the metagalaxy and the atom: some—always and everywhere, and others—only within limited territories.

Each conservation law of modern physics is associated with a special type of symmetry. Incidentally, it is necessary to point out that the term "symmetry" in physics very frequently has a different meaning than when we use it in everyday life.

There is a physical symmetry, for instance, called isotopic invariance. It is inherent in strong interaction and in it alone. It is complied with, for instance, by nuclear particles—nucleons—i.e. a proton and a neutron. Whether a neutron interacts with a neutron, or a proton with a proton or a proton with a neutron, strong interaction is the same with any combination of partners. Meanwhile, one is a little lighter, the other is somewhat heavier, one has a positive charge, in the other the electrical charge equals zero. So let us put their differences aside, and assume that the proton and neutron are two different states of the same particle—the nucleon. We shall equate them, so to say, in everything, except electromagnetic charge, but, of course, we shall stipulate this exception.

In the language of geometry we can formally represent the transition from a proton to a neutron as turning it in a certain isotopic space. We turned the proton and it occupied a new position in this space; from a particle charged positively, it is converted into a neutral one. Very likely, only this turn in a sufficiently arbitrary space is all that has survived in the isotopic invariance of the ancient geometric foundations of symmetry.

Such a physicogeometric operation performed on the nucleon can serve as a model by means of which it will be easier to clear up what the physicists have in mind when they speak of symmetry.

Two paragraphs earlier it was said that the proton and neutron were equated under definite conditions. But this is not all. Any physical symmetry signifies equality, and even more—identity. Of what? Why, particles, physical fields, physical systems, or what you have.

The most, perhaps, simple and obvious rule is: the results of an experiment do not change from the fact that it is transferred to another place if the rest of the previous conditions are maintained.

This is called the symmetry of vacuum with respect of displacements in space.

If the same experiment is conducted several days later (again with the other conditions of the experiment remaining constant), we are not at all surprised to obtain the same results. Here again we have physical symmetry, but this time with respect to displacements in time. Incidentally, it is such simple and even obvious, on the face of it, symmetry that is the basis for the mass and energy conservation laws, which are not at all so obvious to observers.

Just imagine, further, that a certain experiment yields, upon being repeated, a different result, notwithstanding the careful maintenance of all the conditions. What does this mean? Only that time itself changes the nature of the experiment, changes the physical conditions and, consequently, the amount of energy might not be conserved. But such things do not happen.

There is also symmetry with respect to the turning of a physical system in space, and also relatively more complex methods of changing the circumstances in the conduction of an experiment.

It is proposed, by the way, that Newton's law of universal gravitation be dealt with as following from a definite physical symmetry. Before this law was discovered, writes Paul Dirac, the world was in some way two-dimensional to people. When motion was directed upward or downward, the forces of gravity interfered, whereas the third dimension differed from the other two in principle. You could not equate motions along the length or the width, on the one hand, and motions up and down in a gravitational field, on the other.

Newton's formula yields the correction to the terrestrial (or other) gravity, which, when taken into account, enables these motions to be identified.

To be sure, all these conservation principles, that become more and more complicated in our conceptions, are expressed by elegant formulas on paper. These formulas take into account the conditions for the observance of symmetry and its allied laws.

> It is often said that the objective of physics is the explanation of nature, or at least of inanimate nature. What do we mean by explanation? It is the establishment of a few simple principles which describe the properties of what is to be explained. If we understand something, its behaviour—that is, the events which it presents—should not produce any surprises for us. We should always have the impression that it could not be otherwise.
>
> *Eugene Paul WIGNER*

What ingenious mathematical transformations scientists contrive, it would seem, only to find likeness in what is different, to equate what looks unequal.... The turning of a proton in isotopic space, against such a background, looks like an exceptionally simple operation.

And how can all this be put into words, and words alone? Here an old friend of mine, a physicist, one having a doctor of science degree for many years, came to my assistance.

"Everything is quite simple," he said, "Each physical phenomenon takes place against a definite background, in a definite coordinate system, like any play on such-and-such a stage among such-and-such scenery. The equations describing the phenomenon, describe both its background and its coordinates. The same play can be produced with various scenery. You can build a house on the stage, put trees into tubs or simply, as in Shakespeare's time, fasten a stick on the wall of the scenery with the signs: "A Tower", "The Forest" or "The Sea". Shakespeare's *Hamlet* was an illustrious tragedy on the stage of the Globe Theatre in the 17th century and is still one on a motion picture screen of the 20th century. It manifested, speaking the language of physics, invariance, that is, invariability. It demonstrated the power of a certain conservation law: the law of the conservation of art, conserving the force of its influence upon being displaced in space and time."

But the stage and the scenery can be changed so that they begin to hinder the play. The sign with the word "The Sea" can be displayed at the place where a graveyard is required. It presents no difficulty (though it is unpleasant) to imagine that the whole stage can be encumbered with pyramids, staircases and folding screens that cannot handle the roles of at least symbols of reality, preventing the actors from playing their roles and the audience from taking in the relatively little they can, nevertheless, see.

The law of the conservation of art ceases to be complied with under such conditions. Thus, in essence, the equations of physical symmetry are precisely what stipulates in which cases a change in the physical stage does not matter to the play—a physical process—and in which it does. And I repeat that behind all this is what is called the symmetry of properties of vacuum.

> Symmetry, in the broad or narrow sense, depending on how you define the meaning of this concept, is the idea by means of which mankind has endeavored through the centuries to understand and establish order, beauty and perfection.
>
> *Hermann WEYL*

The conservation laws, and today over fifteen are known, are severe and masterful. Each discovery of a new law, not only signifies an extension of our sphere of knowledge, but also leads to the establishment of new rules that forbid the possibility of certain events in the world and, thereby, the achievement of certain aims that previously seemed feasible. We have left in the past our dream of a perpetual motion machine, our dream of H. G. Wells' Cavorite, and others. In writing their book *Monday Begins on Saturday*, mentioned earlier, Arkady and Boris Strugatsky were most likely musing over the fact that with the growth of our knowledge we comprehend more and more the limitations of our potentialities. At this point they introduced the character Sabaoth Baalovich Odin, Manager of the Department of Engineering Services of RIPHRAPH, the Research Institute for Phantasmagoria and Rationalized Phenomena, and also Consulting Engineer of the Kitezhgrad Magical Appliances Plant. Formerly, this bearer of a divine "Christian" name, patronymic and surname had been the leading wizard of the globe. "And somewhere in the middle of the 16th century he truly became all-powerful. After obtaining a numerical solution of the integral-differential equation of Supreme Perfection, derived by some Titan way back before the Ice Age, he acquired the capacity to perform any miracle. He could do anything. And he could do nothing, because the boundary conditions of the Perfection equation contained the requirement that the miracle must not harm anyone: not a single conscious being, not on the earth or any other part of the universe. Nobody, not even Sabaoth Baalovich, could conceive of such a miracle."

In addition, the Strugatskys' RIPHRAPH is not a bad model of any not bad research institute. And to a certain degree, science finds itself from time to time in the same predicament as Sabaoth Baalovich. The most fundamental laws of nature specify, like that fantastic equation of Supreme Perfection, certain boundary conditions that must not be transgressed. They are boundary conditions called the conservation laws.

Mathematics for Physics

> ...Geometry was invented, not for pure philosophizing, but for everyday use, and the basis for its origin should be preserved.
>
> *Sir Isaac NEWTON*

The American physicist Eugene Paul Wigner, a Nobel Prize Winner, has a paper called "The Unreasonable Effectiveness of Mathematics in Natural Sciences". He has here a quite witty definition of mathematics: "Somebody once said that philosophy is the misuse of a terminology which was invented just for this purpose. In the same vein, I would say that mathematics is the science of skillful operations with concepts and rules invented just for this purpose."

Admiring the brilliant examples of the achievements of this strange science, Wigner writes: "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope it will remain valid in future research and that it will extend, for better or worse, to our pleasure, even though perhaps to our bafflement, to wide branches of learning."

I think that you also felt in these lines, inspired with deep emotion, not only joy, but a certain uneasiness, or maybe even sadness. Not only because of the new baffling problems, hardly to be troublesome for our Nobel Prize Winner. Wigner was disturbed by the circumstance that for him the effectiveness of mathematics in the natural sciences remains unfathomable, that he could not explain on what such an effectiveness is supported. In reading this work by Wigner, it really seems sometimes that he fears, from time to time, that in the future such a splendid property of mathematics might cease to be manifested with its previous miraculous power.

But, to all appearances, there is no such threat to physics.

Twenty-three centuries have passed since Euclid wrote his *Elements*, in which he constructed that system called Geometry that we study in school up to this day. (Incidentally, Newton used Euclid's *Elements* as a pattern in writing his main work.)

Twenty-five centuries have passed since Pythagoras stated that "Numbers rule the world".

Many thousands of years have passed since mankind learned to count and to draw geometrical figures. Reminders of those times are kept by stones and clay shards with intricate ornaments saved by the soil for archeologists to find. A. P. Okladnikov, member of the USSR Academy of Sciences and one of the most eminent Soviet archeologists, wrote about such ornaments that: "Their maker succeeded in overcoming ancient inertness in his way of thinking and his chaos of associations. He put order into his impetuous chaos of impressions. He selected that which was essential to him, most important, and expressed it all in abstract form by symmetrically placed geometric lines. The clear instead of the vague and hazy, order instead of disorder, logic instead of vague emotions and gleams of understanding—such is the objective meaning of this most ancient pattern of ornamentation."

From its very beginning, mathematics, even before it became strictly speaking a science, was closely associated with reality and, what is more, with the everyday lives of people, with their vital needs. Frederick Engels noted that: "The concepts of number and form have not been derived from any source other than the world of reality. The ten fingers on which men learnt to count, that is, to carry out the first arithmetical operation, may be anything else, but they are certainly not a free creation of the mind.... Like all other sciences, mathematics arose out of the *needs* of men...."

No matter how abstract Euclid's constructions were and how out of touch they were at first sight (and even, possibly, in Euclid's own opinion) with the requirements of everyday life, these constructions were begotten by reality and were bound to it no less than the first ten numbers to the fingers. This bond has been preserved to our day.

In the 20th century the proposition of the nonaccidental and profound bond between mathematics and the experimental sciences was categorically maintained by John von Neumann, the founder of game theory, the originator of automata theory, who made a huge contribution to quantum mechanics and the development of the first electronic computers. Von Neumann wrote that some of the most brilliant ideas of modern mathematics (being sure that they were its best ideas) can be distinctly followed back to their sources in the natural sciences. He noted that mathematical ideas, once they have come into being, acquire an independent, autonomous existence. They can best be compared with works of art, complying with purely aesthetic appraisal, than with something else.

Then von Neumann warns of the extremely grave danger that an alienation from experimental science threatens mathematics with. It, he contends, is the danger of degeneration. The only salvation is to return to experiment as a source of ideas.

Mathematics demonstrates its capability to derive such new ideas, among others, from research on quantum mechanics, thereby maintaining its freshness and vitality.

You cannot help but note that this chapter is rich in quotations. What can be done: when we are beginning to deal, not with physics, but with mathematics itself, it is especially difficult to manage with words alone (as we agreed at the very beginning), and one involuntarily longs to cite more frequently at least words confirmed by the high authority of the person who said or wrote them. It has been, of course, known for a long time that, in itself, the support of even the highest authority is of no avail. I am guided here, not by the words, but by the deeds that back the words. Mathematics was extolled by people for whom it was a science and a handicraft at the same time, a game and an art: at once the most abstract and the most realistic art in the world.

All that has been written so far in this chapter is only the introduction to a turning point in our story of physical vacuum.

The role of mathematics in physics is much more important than merely to supply it with equations, to provide it with diagrams and calculations. In his definition (witty, I repeat) of mathematics, Wigner mentions, not only skillful operations and rules, but concepts invented just for this purpose. In each jest, as they say, there is a grain of truth. The advent in physics of concepts taken from mathematics, "invented" by mathematics, plays an exceptionally vital role.

I shall attempt, only with words as previously, to demonstrate by examples how a mathematical concept develops in physics. But not in physics in general; only in application to the problem of physical vacuum, to certain ways in which it is described by mathematics.

What, from the mathematical point of view, is an elementary particle, to what available geometric figure can it be likened? (Here we stipulate: we shall call elementary particles, according to up-to-date physics, only those in which no internal structure can be found; this excludes, as you already know, the highly merited proton and neutron, pi-mesons and other particles that have, according to the latest concepts, an internal structure made up of quarks.)

Thus, what does an elementary particle look like? Of course, like the good old point, the simplest of geometric figures (incidentally, it has already been mentioned in this book that the world of quantum physics is much simpler than our macroscopic world). True, a geometric point, according to Euclid, has no length or width or height (depth), whereas an elementary particle should have all these attributes. But for us a point is only the designation of a particle, a word taken from the language with which nature speaks to mankind.

To have the name more closely fit what it is applied to; for the designation to be closer to the designated and correspond to it more exactly, we shall call an elementary particle, not simply a point, but a physical, or material, point. In science such points first appeared in the 17th century, and were almost immediately supplied with an interesting set of properties. Since a point is material, it must have mass. Since a point travels, it must have a velocity. Of course, even before mass and velocity, a point had to have coordinates to specify its position in space.

But in the 17th century, it is obvious, they knew nothing of elementary particles, nor could they know. Even the proposition that matter consists of atoms, that there is a limit to its divisibility, remained undecided, retaining the rank of a hypothesis, though by this time it was over twenty centuries old.

What, then, was called a physical point in the physics of that time? A great variety of things were thus designated. In some cases, for instance, the moon and the earth and even the sun itself could serve as material points. Newton's formula of the law of universal gravitation includes, not counting the coefficient (the gravitational constant), only the masses of bodies attracted to each other by gravity and the distance between their centres of gravity. Hence, when solving a particular equation, these centres can be taken as material points endowed with exceptionally sizable masses. I did not pick out this example by chance. It should prepare you for the somewhat similar operations, though absolutely incomparable in scale, that a physical point is subject to in our time.

At the turn of the century physicists began to discover elementary particles, without grasping very well at first which of them really were elementary and which were compound.

It turned out that particles, of all things, can be most conveniently dealt with as material points. Mathematicians describe them as existing in ten-dimensional and even thirteen-dimensional space, the number of dimensions being specified by the amount of numbers required to impart all the characteristics of the elementary particle: three numbers determine its position in space; three, its velocity, etc. These multi-dimensional spaces are, of course, only phrases in the language of mathematics, only representations of our ordinary three-dimensional space or four-dimensional space-time.

(To keep you from attaching too great a significance to the multi-dimensionality of space, it is worth noting that multi-dimensional spaces can be conveniently resorted to, for example, in describing the motion of a gas molecule, and in many other cases.)

But let us proceed. In geometry, sets of points form figures. In nature, elementary particles (in any case, some of them) gather together into atoms.

The simplest of the atoms known in nature is that of hydrogen. Its nucleus—a single proton—contains three physical points, three quarks, with a physical point—the electron—travelling around them. Some time ago physicists found that the atom, strictly speaking, does not consist of a nucleus and an electron. The atom exists only owing to the omnipresent virtual particles, virtual photons in the given case, that the proton and electron exchange. In any atom the virtual clouds of separate particles, which we have already mentioned, join together into a general cloud, into a certain supercloud. This means that the hydrogen atom actually consists of three physical points—quarks—a physical point electron and a great multitude of virtual photons. How can we call this last in the geometric language?

An analysis indicated to physicists that too little is known about virtual particles to call them, each one separately, physical points. It is impossible, for example, to determine, in principle, the place where any one of them is located.

As you recall, we just cleared up the fact that we know much too little about an elementary particle, not having found that it has any internal structure; much too little to grant such a real particle the right to have a claim on the name of any geometric figure except the simplest of them: the point. But it is also impossible to find the structure of the virtual supercloud of the atom. In a word, in clearing up the situation, we come to the conclusion that we know too little about the cloud of virtual particles in an atom to conceive of it as being any other figure besides a point. This means that it remains to designate the cloud, filling up part of the vacuum in the atom, as a point. But this, obviously, should be a point that is not exactly ordinary. What kind then? Physicists would have been in a difficult situation if it were not for that same unreasonable effectiveness of mathematics that Wigner so admired with some alarm.

The fact is that the mathematicians already had suitable extraordinary points in stock. They appeared when, at the turn of the century, set theory entered into topology, the science of spatial shapes, and engaged itself in putting it into order. The new branch of science—set topology—was able to make geometry itself much more rigorous and accurate. All of a sudden it turned out that in the system of geometric figures developed by set topology, special points, called open points, are indispensible. S. Smirnov explains this concept as follows: "Recall Gogol's story called *The Nose*. It has as a real character a part of the human figure that is not capable of independent existence. Such parts of figures that are not themselves figures are found in geometry; even a point may prove to be 'a nose without an owner'. In the language of geometry, these 'fragments of figures' are called open sets." Points can also be open.

And then the mathematicians showed that they were heirs, not only of Euclid, but also of those ancient discoverers of arithmetic that had not yet learned to separate the number of fingers from the fingers themselves. Having discovered such an impossible, it would seem, mathematical abstraction, they immediately began to search for some object in the real world that could correspond to the new word in their language. Incidentally, the lack of a suitable object to apply the new concept to served as a forcible argument for the mathematicians that objected against the introduction of the new concept. Finally, such objects were found. More exactly, they were calculated and revealed by theoretical physicists. These were the clouds of virtual particles.

This brings to mind the words of the famous Russian scientist and engineer, Aleksei Nikolaevich Krylov, member of the St. Petersburg and USSR Academies of Sciences, which are as if directly describing the story related above (actually, a thousand similar stories).

"...A geometer," wrote Krylov, "that develops new mathematical conclusions can be likened to a certain imaginary general-purpose toolmaker, who makes tools for any purpose and stores them in the toolroom. He makes everything beginning with a blacksmith's anvil and up to the finest microscope and chronometer. The geometer develops methods for solving problems, not only those posed by modern requirements, but for future ones. Such that may arise, perhaps tomorrow, perhaps in a thousand years."

Thus, these ownerless open points were found to be, so to speak, exact portraits of the same clouds of virtual particles that have attracted our attention over a great many pages.

Virtual particles, appearing and immediately vanishing inside the cloud, remind one of our schoolroom concept of a very ordinary gas. Smirnov writes, "...A gas differs from a single isolated particle primarily because it can be in many different states; it can be more or less heated, occupy more or less volume, and finally, under certain conditions it can condense into a liquid and even freeze, i.e. solidify."

Similar changes can also take place with our clouds of virtual particles. From this follows the possibility of a great diversity of properties of our open physical points. A diversity of properties of ordinary real elementary particles (they are closed physical points) is not provided, so to say, by their own internal properties, and appear as a result of interaction with open points.

As a matter of fact, we are, with the use of new words and to some extent a new language, repeating what we have already said in this book when we associated the properties of ordinary particles with how they interact with virtual particles.

The following, for example, is how the explanation of from where particles acquire mass sounds in the new language.

Besides the clouds of virtual photons in atoms, we know of "universal clouds" of virtual particles of all possible kinds, clouds that fill, not only a part of the volums of atoms, but the whole volume of the metagalaxy. But even in such a supergigantic cloud of, for instance, virtual electrons, physicists have failed to discover "brilliant individualities" and to reveal the internal structure of the cloud. Well then, we shall have to represent the cloud of virtual particles, entirely regardless of the region it occupies, again by a point, only an open one. According to the kinds of virtual particles involved, a vacuum can be represented by a number of open points corresponding to the number of kinds of particles. Our multiple-ocean Dirac vacuum endures, as a result, a truly humiliating transformation: in mathematical description, each of the oceans becomes only an open point.

One of these world-wide oceans (also an open point) is formed by Higgs' bosons.

We give the floor again to Smirnov: "Suppose that the 'Higgs universal cloud' can exist in two different states —'gaseous' and 'liquid'—which have different energies, with the transition from the gaseous to the liquid state taking place with the evolution of energy (like when ordinary water vapour condenses into water). Finally, let us assume that the Higgs cloud interacts differently, when in these states, with elementary particles. When it is a gas, the interaction is almost imperceptible; when it is a liquid, the particles acquire mass. All the electrons in the metagalaxy have the same mass; the same is true of the protons, etc. This means that each particle of any kind interacts with the Higgs cloud as with a single whole: with a 'Higgs open point', which in our age is in the 'liquid' state. This refers to 'now', but previously it was different: the Higgs cloud was 'gaseous', and all the elementary particles had zero mass. Then the 'gas' turned into a 'liquid' with the evolution of a huge amount of energy; this was one of episodes of the Big Bang...."

As you evidently recall, we have already discussed this situation, only in other words. We can, after Niels Bohr, call such descriptions complementary to each other.

The Fruitbearing Void

Could it not be that vacuum begot the universe as a whole at some time in the dim past as it creates particles today? And how could this be done without violating the conservation laws? According to a proposal of G. I. Naan, member of the Estonian Academy of Sciences, the universal void could have created a pair of worlds simultaneously, a pair of metagalaxies, if only by analogy, with the creation of an electron-positron pair of virtual particles by vacuum.

This hypothesis, besides all other matters, seems to provide an explanation for the following difficult, and so far unsolved, problem, notwithstanding the multitude of interesting hypotheses advanced: why does the world we know consist, as far as we can judge, practically only of matter? No accumulations of antimatter have been discovered, notwithstanding the searches of the astrophysicists, either in the vicinity of the solar system or in the distant "outskirts" of the metagalaxy. At the same time, known physical laws seem to indicate that, in the Big Bang, matter and antimatter should have appeared in equal amounts.

G. I. Naan writes: "A crude model of vacuum can be conceived of as an infinitely great supply of energy of one sign, compensated by as large a supply of energy of the other sign."

Two worlds that came into existence simultaneously should have differed by the signs of their charges (like an electron and a positron in a pair of virtual particles). One of them turned out to consist of matter, and the other of antimatter. We live in the first of these (according to our reckoning), but "somewhere", maybe, there is just as large and complicated antiworld, without which our world would "simply" not be. And we can, repeating and paraphrasing the well-known Soviet poet Andrei Voznesensky, contend roughly the following:

No wise men without foolish ones,
Oases without Karakums,
And without Them, just where were we?

Antiworld came that world might be.
When that nocturnal moment started,
Antiworlds, that's when you departed.

In a word, the material medium that prescribes laws to "ordinary" matter began its relations with this matter by creating it. I repeat, just in case, that such a supposition is only a supposition, one of the hypotheses. Nevertheless, how can we refrain from rendering due praise to Mighty Physics, capable of proposing such hypotheses.

Naan claims that his hypothesis answers the most cardinal of all questions: why does the universe exist? The answer is: the universe exists because "nothing" is unstable and polarizes into "something" and "antisomething".

> They are worlds like ours.... Some of them less; many of them a million times greater; and some of the least sparkles that you see are not only worlds, but whole clusters of worlds turning about each other in the midst of space. We do not know what there may be in any of them; perhaps the answer to all our difficulties or the cure of all our sufferings: and yet we can never reach them; not all the skill of the craftiest of men can fit out a ship for the nearest of these our neighbors, nor would the life of the most aged suffice for such a journey. When a great battle has been lost or a dear friend is dead, when we are hipped or in high spirits, there they are unweariedly shining overhead. We may stand down here, a whole army of us together, and shout until we break our hearts, and not a whisper reaches them. We may climb the highest mountain, and we are no nearer them. All we can do is to stand down here in the garden and take off our hats; the starshine lights upon our heads, and where mine is a little bald, I dare say you can see it glisten in the darkness. The mountain and the mouse. That is like to be all we shall ever have to do with Arcturus or Aldebaran. Can you apply a parable?... It is not the same thing as a reason, but usually vastly more convincing.
>
> *Robert Louis STEVENSON*

It should be specially stipulated that, according to Naan, the world and antiworld come into existence simultaneously and in correspondence. Subsequently they exist in different, so to speak, space-time frameworks, and their interaction is impossible.

Something and antisomething owe their existence to each other and to the vacuum. Together they form the universe; such a comprehensive-symmetrical universe consists, on an average, of emptiness alone.

At least twice in the 20th century outstanding scientists attempted to find in the material medium of the world a constant, independent of all influence, source of spontaneously nascent ordinary matter.

In 1912 the famous German physical chemist Hermann Walther Nernst proposed the assumption that in each hundred litres of the world's material medium (Nernst, as formerly, called it ether), during each thousand million years (or a somewhat longer time), there appears one—only one!—atom of uranium. Then, after decaying, this atom of uranium provides for replenishing the universe with other elements of Mendeleev's table. Their energy, according to the Einstein formula $E=mc^2$, replenishes the stores of energy of the world and saves the universe from heat death, which, it was thought at that time, was foretold by the laws of thermodynamics.

The end result of disintegration of the atoms, according to Nernst, consists of particles of the same universal medium, particles of ether. It is notable that in calling this medium ether, Nernst, much closer than he usually did, associated it with the general evolution of matter in the world, turning the ether into both the great-grandparent of ordinary matter and its grave-digger.

Then in 1946 the English astrophysicists Hermann Bondi and Thomas Gold proposed that as the universe expands matter appears (without antimater) spontaneously in space from physical vacuum without the influence of any special external fields. Their calculations, supplemented by the English astrophysicist Fred Hoyle, were quite good mathematically, the idea was ingenious, and the amount of matter created in such a way was so small that, it seemed to the investigators, one could become reconciled to the situation. But even though matter was created extremely rarely, it was still an encroachment on the law of conservation of mass and energy.

Scientists, in general, regarded such a hypothesis with severe disapproval, but it did explain certain observed facts so very well.

It would seem very difficult to test his hypothesis: just try to find out whether any new matter has been created, when it was suposed to appear in meagre amounts over huge intervals of time. Nevertheless, observations during the last two decades are exactly what has disproved such a hypothesis. But the observations concerned something entirely different. It turned out that the number of radio stars in the metagalaxy was greater in the past than at present. But the "continuous creation" of matter, according to calculations, should have led, on the contrary, to their increase or, in any case, to the conservation of the number of radio sources in space at the same level.

Even before the hypothesis was disproved by facts, it was actually rejected from theoretical considerations. No one is allowed to violate that holy of holies of physics—the law of conservation of mass and energy. The great majority of physicists played the noble role, in this situation, of the Professor from *Twelve Months*, the popular Russian fairy tale and children's play by Samuel Marshak. There, if you recall, the Professor told the little Girl-Queen who wished to repeal a law of nature that it was not in her power to do so.

World physics as a whole flatly rejected any encroachment on the conservation law. What cannot be, cannot be. Physicists like "mad ideas", only each time there is, as in Hamlet's madness, a method, and what a clear-cut one!

But from the fact that vacuum cannot create particles spontaneously, offhand, it does not at all follow that it is altogether incapable of such creation under definite influences.

Vacuum responds to action of an external field; it changes, its structure is rearranged, and its properties are altered. We have already discussed the polarization of vacuum. Indeed, as a matter of fact, in all encounters of vacuum with particles, not only they and the forces that control them are changed, the vacuum itself is changed, if only because in our infinitely complicated world all things are in interaction, acting reciprocally.

What will happen if we subject our vacuum, not just to any field, but to an extraordinarily strong field, a field carrying sufficient energy to transform at least some virtual paticles into real ones? What, in fact, do these ephemeral ghostly particles lack to become embodied in flesh and blood, and change their quite conditional rank to a more official status in the microscopic world? What they lack is just energy. Furnish sufficient energy and "Dirac's Sea", the great ocean of virtual particles, will take to creating ordinary matter plus ordinary antimatter in accordance with the famous formula $E = mc^2$, where E is the energy, m is the mass and c is the velocity of light.

In our case the formula takes the form $m = E/c^2$.

In our diverse universe there must be quite a few places where energy is applied to vacuum in exactly the required manner and with exactly such results.

Energy for the "production" of real particles from vacuum may be furnished by the gravitational field and by the electromagnetic field.

As far back as 1939 Erwin Schrödinger (the same German physicist that derived the classical Schrödinger equation of quantum mechanics, which will bear his name in the centuries to come) theoretically substantiated a situation in which particles were supposed to be created from vacuum. But then. . .it sometimes happens that in physics an equation (or an experiment) turns out, at least for some length of time, to be wiser than its creator: he cannot bring himself to acknowledge his own objectively correct results. This is exactly what happened with Schrödinger; he considered the feasibility of particle creation from vacuum to be simply a shortcoming of the theory on which his reasoning and calculations were based.

Over forty-five years have passed. During this time, the world over many dozens, if not hundreds, of scientific papers were published that discuss various suitable (or unsuitable) circumstances for particle and antiparticle creation from vacuum. Such pairs could appear from vacuum in the initial stage of evolution of the universe. They are created now as well—wherever nature applies fields of monstrous strength to vacuum. Without taking into account the effect of particle-antiparticle pair creation it is impossible, for instance, to understand the physics of the now famous "black holes".

Naan's hypothesis of the creation of the world and antiworld from vacuum is not supported by Yakov B. Zeldovich, member of the USSR Academy of Sciences. But Zeldovich resorted to the idea of particle creation from vacuum in strong gravitational fields to explain why the properties of our universe are strikingly uniform throughout the extent known to us. The initial universe, immediately following the Big Bang, was evidently not as uniform as it is now; particles begotten by vacuum averaged its properties. In a word, even if our universe was not created wholly from vacuum, it, nevertheless, is obliged to vacuum for its present structure and arrangement.

The victories of quantum theory, and still more the fact that we have become accustomed to these victories and are aware of their soundness, have led to the following acknowledgement: vacuum really is capable of creating "genuine" matter. This requires the application of an electromagnetic field of extremely high intensity. True, the intensity, or strength, required for a "vacuum explosion" is still technically unattainable, but, as they say, it is a matter of principle. Such powerful electromagnetic fields apparently do exist somewhere in space.

How keenly physicists would like to see the creation of real particles from vacuum, not in space, but on the earth, in their laboratories!

According to Coulomb's law, the intensity of a field between electrical charges increases, not only with an increase in the charges, but also with a decrease of the distance between them. We are still unable to produce charges so powerful that the field between them causes a vacuum explosion, so let us resort to situations in which the same field intensities are produced by the small distances. Such a situation may occur if two uranium atom nuclei are brought together to a distance of 10^{-11} cm between them, that is only several dozens of times greater than the diameter of the nuclei themselves. For this purpose the atomic nuclei have to be pushed towards each other, peeling them of electron shells like a potato of its skin.

Practically, this involves the bombarding of a target of heavy nuclei with beams of heavy ions. At the instant when the "missiles" hit the "bull's eye", two nuclei may happen to be sufficiently close to each other to produce the required field intensity and awake the sleeping vacuum.

The preceding paragraph begins with the words "practically...involves". As a matter of fact such experiments are being conducted and the physicists that perform them believe that in the near future they will gain their ends.

It is doubtful, however, that the creation of real particles from vacuum in a gravitational field will be observed in a laboratory on earth even in the relatively distant future. We are incapable of manipulating gravitational charges like we do electromagnetic ones (we shall not, however, forget the old precept: never say "never").

But superpowerful gravitational fields do exist in space. A physical experiment can be replaced by astronomical observations and by comparing astrophysical data with theoretical predictions.

Just, how, specifically, can the transformation of virtual particles into real ones take place? In what way could these wraiths of the microscopic world lose their phantasmal form? To clear up this matter we shall begin with a book written by Arkady B. Migdal, member of the USSR Academy of Sciences, and published in 1978 (in Russian by the Nauka Publishers). It is called *Fermions and Bosons in Strong Fields.*

Among other matters, the chapter "All the Powers of the World" dealt with bosons as particles and groups of particles that are capable of uniting into well-coordinated collectives. Then, we postponed a more detailed discussion on bosons. This is the exact place for such a discussion, as well as for information on what fermions are.

Bosons and fermions are the two broadest classes into which quantum mechanics divides all the particles it is in charge of. Whereas bosons owe their name, as you already know, to the Indian physicist Satyendra Nath Bose, fermions were named after the famous Italian physicist Enrico Fermi.

The main difference between the two classes is the magnitude of their spins. When the concept of spin was introduced into theory, it was supposed that an electron resembles a rotating top; spin characterizes such rotation. Later, this analogy turned out to be incorrect, but any other comparison, even for a popular explanation, could not be found in our great world. It remains to cite the handbook definition: "the intrinsic angular momentum of elementary particles, having a quantum nature and not associated with the motion of a particle as a whole.... Also called spin is the intrinsic angular momentum of an atomic nucleus (and sometimes an atom) ...."

The spin of a boson is equal (in special units) to zero or to an integer; the spin of fermions is, as the physicists say, half-integer and equal to 1/2, 3/2, etc.

The behaviour of a particle with respect to others like itself depends to an extraordinary extent on whether its spin is integer or half-integer. This is exactly what determines the ability or inability of each elementary particle to "tolerate" in its vicinity, in its physical system, its own twin—exactly such a particle and, moreover, in the same energy state.

Bosons are particles that are easy to live with and are tolerant; in their systems twins do not bother one another.

Similar fermions can be likened to two straggler bears which cannot get along together in a single den.

An example is the electron. Its spin is 1/2, i.e. it is a fermion. In an atomic shell the electrons "coexist", but among them you cannot find two that are in exactly the same energy state. If an energy twin of one of the host electrons appears in an atom, even if only as the result of an exchange of electrons with another atom in the course of a chemical reaction, the guest electron, in order to rid itself of a dangerous resemblance and to remain in the atom, must radiate a part of its energy in the form of photons.

As a matter of fact, this simply agrees with the Pauli exclusion principle. The principle that played, as has already been mentioned, a most important role in the appearance of the "Dirac Sea" in physical theory, even in the first version in which it was a bottomless ocean of electrons with negative energy.

Fermions are electrons and nucleons, quarks, the neutrino and mu-mesons and a great multitude of other particles, as well as bound systems of an odd number of fermions, say, for instance, atomic nuclei with an odd nuclear charge, etc. Also belonging to fermions are quite a number of representatives of the diverse family of quasiparticles. It might be said that we consist entirely of only fermions (as we know, the atom consists of only fermions: protons, neutrons and electrons). But this is not so because a bound system of an even number of fermions is transformed into a boson. This has already been demonstrated by taking a pair of electrons in a superconductor as an example. An atomic nucleus with an even nuclear charge, for instance the nucleus of oxygen, also turns out to be a boson.

Migdal's book deals especially with the reconstruction of a vacuum in strong external fields. It was written, of course, for physicists. But in a booklet for the layman called *In Search of Truth* (published in the same 1978 in Russian by the Znaniye Publishers) the academician gives an idea of one of the processes that he analyzes, fully equipped with pertinent theory, in the scientific book.

The following is a long quotation from the booklet.

"Assume that the external field has the shape of a wide potential well. We shall now explain what a potential well is. The simplest example of a potential well is a pit dug at the surface of the earth. At the bottom of the well, the potential energy of a particle or, for the sake of definiteness, a stone, is minimal. As the stone drops into the well it acquires kinetic energy, equal to the difference between the potential energies at the top edge and the bottom of the well. As the well (pit) is deepened, the energy, developed by the stone in dropping into the well, increases. In vacuum, all possible kinds of particles are created and disappear at the upper edge of the well. For such a 'virtual' particle to become a real one, it is necessary to impart to it, according to Einstein's famous formula, an amount of energy equal to mc^2, where m is the mass of the particle and c is the velocity of light. The energy imparted by the field to the particle when it falls to the bottom of the well can be used either to increase the kinetic energy of the already created particle, or to transform a virtual particle at the upper edge of the well into a real particle at the bottom of the well."

The possibility of the transformation of virtual particles of vacuum into real particles is by no means news, even to the readers of this book. But in the situation discussed by Migdal, vacuum creates matter so that a star supplied with this matter acquires a fantastic density, several times greater than matter has in an atomic nucleus.

The source of the strong external field, in the given case, is a neutron star. It is in its powerful field that the virtual particles, "falling" into an enormously deep potential well, are transformed into real ones.

Primarily, such a transformation occurs with pi-mesons (called pions for short). Owing to pion condensation there comes a point when in the heart of the star, at its very centre, a nucleating centre of superdense matter appears. This nucleating centre impetuously grows, spreading out in thousandths of a second, until the whole mass of the star goes over to this new state. This may be followed by a monstrous explosion.

We shall not go into the finer details of what is going on, the most important of the results of the explosion for us is that the incandescent outer part of the star (its shell) can be thrown far into space.

This event, possibly, is observed on earth as the outburst of a supernova. In ancient times such outbursts were recorded in chronicles and annals. Memories of them were kept, not only by astronomers, but by historians as well, though the latter were not versed in astronomy. And no wonder that they did! During the maximum phase of the outburst, the flare of a single star becomes brighter than the light of a thousand million stars like our sun.

For quite a long time the outburst of a supernova has been explained as a result of nuclear reactions accompanying the formation of a neutron star. Migdal proposes, in essence, that there are two types of supernova outbursts. The old explanation is correct for the first of these types. His new explanation concerns the second type. As a matter of fact "it is possible that not all supernova outbursts can be reduced to these two types. Further analysis of observational data should enable us to establish whether it is necessary to search for some other explanation," wrote Migdal.

Thus, events occurring in vacuum may owe their origin to the brightest—at least for a short time—of stars.

The creation of particles by vacuum is the specific reason that the density of neutron stars increases several times until, finally, an outburst becomes feasible. The existence of pion condensation may have other consequences as well with respect to our conceptions of space.

One of the most "fashionable" topics in science today involves the problem of "black holes". Theory seems to indicate that an extremely dense neutron star (developed as a result of impetuous implosive contraction of stellar matter, an implosion known as gravitational collapse) may, after again undergoing such a collapse, turn into an immense gravitational trap: the force of gravity near the surface of this body in outer space becomes so powerful that even light cannot escape its chains. Zeldovich called this monstrous formation a gravitational coffin.

A black hole becomes an object that sucks in particles and gas; its circumference along its equator should be as many times greater than nineteen kilometres as its mass is greater than that of the sun. Black holes may be, according to present-day concepts, quite tiny, of a mass equal to that of several hundred up-to-date ocean liners, or they may be gigantic bodies, of a mass tens of millions times greater than the mass of our sun.

Well, and a typical, medium-size "gravitational coffin", as follows from calculations, should have a girth from sixty to a thousand kilometres and a mass three to fifty times that of the sun.

Pion condensation infringes on the right to be the cause of at least a part of these beloved offspring of up-to-date cosmology. Owing to the pions appearing in vacuum, according to Migdal's model, a neutron star can explode at a density that is still insufficient for it to be converted into a black hole.

Then the way to conversion into a black hole is open only to gigantic stars. Their gravitational collapse occurs at a relatively lower density of matter, and their field, owing to this circumstance, is insufficiently intense for the "mass production" of pions and for the initiation of the stage of pion condensation.

If pion condensation does not necessarily lead to the explosion of a neutron star, then the following outlook becomes feasible. At a definite density of neutron matter, the neutrons themselves should decay into quarks, in which case the star becomes a quark one rather than a neutron star. We do not know whether it is possible in principle to achieve such high density in a star.

There should not be too few places in the universe where highly intense external fields stimulate the creation of real particles from vacuum on a very considerable scale. The gravitational field of a black hole, for instance, is sufficiently large so that in its neighbourhood real particles are created from vacuum. Here virtual particles acquire a more or less prolonged lifetime together with the mass that they have a right to in this case.

The English physicist Steven William Hawking and the Canadian physicist Werner Israel explained the thermal radiation of black holes in the following way in an article they wrote for *An Einstein Century Survey.*

A virtual pair of particles can be separated in vacuum: "if a black hole is present, one member of a pair may fall into the hole leaving the other without a partner with whom to annihilate. The forsaken particle or antiparticle may follow its mate into the black hole, but it may also escape to infinity where it will appear to be a particle or antiparticle emitted by the black hole."

Then the authors of the article enter upon a discussion about what shape such radiation might have, and come to the conclusion that a "black hole emits with equal probability every configuration of particles" and can, in principle, "emit a television set or Charles Darwin, but the number of configurations corresponding to such exotic possibilities is very small."

Is the share of particles created by vacuum under the influence of strong fields very large in the universe? Here opinions differ. In one of their papers, S. G. Mamaev and V. M. Mostepanenko reach the following conclusion: "This enables the coming into existence of the universe to be interpreted as an effect of the distinctive instability of the vacuum state of the quantum field." True, in another paper, published in the same year (1978), the same authors, together with A. A. Grib, wrote: "...Results show that the density of the created matter and antimatter for known elementary particles is small compared to the observed density of matter in the universe. It is therefore impossible to explain, at any rate at the present stage of evolution, the creation of all matter in such a way."

But, very likely, there is no contradiction here. In the second case, they are concerned with the "present stage of evolution" rather than the initial one.

Moreover, it is beneficial sometimes to recall the remark made by Richard Phillips Feynman with an elegiac sigh: it is difficult for a person who is not a professional scientist to believe how many arguments can be advanced in favour of each of five or six contradictory theories.

A monograph written by the Soviet physicist A. A. Grib was published not long ago. It had the significant title: *On the Problem of the Noninvariance of Vacuum in Quantum Theory.* Noninvariance means variability or changeability.

Recall our recent discusssion on the transformations associated with physical symmetries. Especial attention should be paid to the following circumstance. In quantum mechanics, one and the same values of observed quantities may correspond to many different states of physical systems. Therefore, the same vacuum effects may be due to different causes. When, for instance, the temperature of a person increases to 39 °C (102 °F) the cause may be any of a great many different sicknesses.

In his monograph Grib analyses the possibility that a great numbers of states of vacuum exist, and what is more, many vacuums that can convert into one another. "One vacuum," writes Grib, "can be obtained from another by a certain transformation."

In their models of vacuum, physicists liken it to a superfluid liquid, a superconductor or a ferroelectric substance. All of these are models, each of which represents only a part of the properties of the original; and the original itself is capable of changing. Grib positively contends that the void has become the "foundation of the world."

It can, of course, be noted—and this remark will to some extent be valid—that the immense vacuum effects in outer space are, so far, more likely to be predicted by theory than to be accurately and conclusively determined in phenomena observed by astronomers.

But astrophysics, even though it deals with the stars, remains in full measure a terrestrial science.

Hannes Olaf Gösta Alfvén of Sweden, one of the greatest physicists and cosmologists of the world, once noted that astrophysics is mainly an application of laws of nature, discovered in a laboratory, to space phenomena. As a matter of fact, the terrestrial nature of the understanding of celestial phenomena is clearly demonstrated by the whole history of science. To discover radio stars it was necessary at least to discover radio waves and, moreover, to learn to generate them. All the opinions of the greatest wise men (really wise men, without a drop of irony) about where the sun and stars got their energy, were quite speculative and quite incorrect before the founding of nuclear physics on earth. In exactly the same way, it was impossible to expect correct hypotheses on the effects of vacuum on the stars and other celestial bodies before vacuum effects, such as the Lamb shift, were observed in the laboratory.

It is very possible that vacuum effects have been literally "striking the eyes" of astronomers for a long time. It is only necessary to understand that certain features in the radiation of at least certain stars are associated exactly with these effects.

I cite an example which, it is true, may seem unpretentious in comparison to the idea of the simultaneous creation of a world and antiworld from vacuum.

A paper by G. G. Pavlov and Yu. A. Shibanov, called "The Effect of Vacuum Polarization on Wave Propagation in Plasma", was published in the *Journal of Experimental and Theoretical Physics,* which is also available in the English translation. The paper dealt with the polarization of vacuum by a strong magnetic field, the plasma referred to being stellar matter.

A magnetic field introduces its order among virtual particles, as we already know, changing the nature of their disposition and, as a result, the vacuum changes its properties. Now photons travel in the vacuum, not like they do in space uniform in all directions, but like in an anisotropic medium, capable of refracting electromagnetic waves. This, according to calculations, should change the nature of radiation of a variety of bodies in outer space, such, probably, as X-ray pulsars and white dwarf stars.

The authors of the paper explicitly state: "To properly interpret observations in the X-ray, ultraviolet and optical ranges, it is necessary to take into consideration the effect of vacuum polarization." They also indicate certain special features of the radiation that follow from their calculations. If astronomers succeed in detecting these features, physicists will obtain the opportunity to investigate vacuum effects that cannot be artificially produced in any terrestrial laboratory at the present time or in the near future.

Beyond the Power of Even Vacuum

You have already become acquainted with certain phenomena that occur or at least could occur in vacuum.

Of value in science, however, are statements not only about things that are, or may be, but also about things that cannot be. Ya. B. Zeldovich wrote a short paper about certain spontaneous processes that cannot proceed in vacuum.

The need of such a paper, in the opinion of its author, arose insofar as certain theoretical physicists regarded precisely these processes as being feasible.

There is a hypothesis about tachyons, particles that always travel faster than light. "Einstein's ban" on exceeding the velocity of light is masterly side-stepped: the light barrier is just as insurmountable an obstacle for tachyons as it is, for instance, for electrons. But, in contrast to electrons (and the rest of the ordinary particles having a rest mass), tachyons acquire energy (and an equivalent mass) in deceleration and lose it in acceleration. Einstein's light barrier is for them the lower limit, rather than the upper one; they live in a "world-the-other-way-round". It follows from equations that tachyons have imaginary mass. There are certain hypotheses that even involve particles with negative mass and energy.

It can readily be conceived (after all that you have already read in this book) how a set of real particles, including ordinary and exotic ones, are created simultaneously in vacuum. A set in which one half of the constituent particles have ordinary mass and the other half have negative mass, so that the total mass of the set equals zero. Well, and the total energy is also equal to zero, as is the total momentum.

Everything would seem to be fine: the law of conservation of mass and energy is complied with, and particles are created from vacuum without the application of a powerful source of energy.

In a word, according to the saying: to eat one's cake and have it.

An excellent situation, one would think. But even in quantum physics you cannot eat your cake and, at the same time, keep it whole. Calculations, carried out by Zeldovich, indicate that a version in which ordinary and exotic particles are spontaneously and simultaneously created is unreal.

Zeldovich concludes his paper explicitly: "There is every reason to suppose that vacuum is stable, and no spontaneous decay of vacuum takes place."

Around and About the Neutrino

The most mysterious of all the particles discovered up to the present, the neutrino, has appeared on the pages of this book time and again on the background of vacuum. You have read how attempts were made, after looking into the history of science, to discern the real features of the neutrino in the hypothetic "ether atom" of Dmitri Ivanovich Mendeleev. Many scientists that advance hypotheses on the structure of vacuum see in neutrinos their future allies with whose aid they will be able to check whether matters stand in practice the same as in their thought experiments. The extremely high penetrative capacity of these particles makes them an indispensible tool in investigating the structure of the microscopic world.

What is, perhaps, most important in the neutrino for the subject of this book is that the theory of the Grand Unification, based on the properties of physical vacuum, requires that this particle have mass.

Today the neutrinos have secured a highly important place in physics. Only they alone of all the elementary particles have won such a high honour as the right to have its own committee in the USSR Academy of Sciences. The Neutrino Committee is headed by Bruno Maximovich Pontecorvo, member of the USSR Academy of Sciences.

In 1980 V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tretyakov and V. S. Kozik performed an experiment in the Soviet Union in the Institute of Theoretical and Experimental Physics. It turned out to be a breakthrough, as they were the first to determine the mass of the neutrino. It was found to be approximately 30 electron volts (more exactly, not over 46 and not less than 14 electron volts).

This experiment will be conducted again and again, and checked and rechecked. Not because somebody does not wish to trust the experimenters; it is simply just too important for the proper understanding of the world at all of its levels, from the micro to the mega level.

If the neutrino really has a rest mass, then of all the elementary particles known to us, only the photon remains without one.

The rest mass of the neutrino solves the old "hidden mass" paradox, also called the Zwicky paradox (named after the well-known Swiss-born American astrophysicist Fritz Zwicky). This paradox consists in the following. The mass of each galaxy is related to its luminosity. From the amount of light emitted by the galaxy (or cluster of galaxies) we can calculate, approximately of course, its mass. This same mass can be determined in a different way: from the velocity of revolution of stars located at different distances from the centre of the galaxy. The latter method should be more accurate because the attraction of all the bodies in this large stellar system affects the motion of the stars in the galaxy.

The mass of a galaxy (or group of galaxies), calculated from its luminosity, may be found at times to be less by a factor of two or even ten than the mass determined from the motion of the stars. Such a difference in results cannot in any way be explained by inaccuracies in calculations. The reason is that only the visible bodies are taken into account in the first case; in the second, the invisible ones are also included. If the neutrinos actually do have a rest mass, then they make their contribution, increasing the total mass of the galaxies.

Each discovery not only answers old questions, but also puts new ones. The discovery of a rest mass for the neutrino is no exception. True, the neutrino was assumed to have a certain rest mass by the physicists working on the theory of the Grand Unification, but not so large as that discovered by the physicists in Moscow. Hence, if the experiment was accurate (and this will be confirmed or denied by further research), the corresponding revisions will be introduced into the theory of the Grand Unification.

The neutrino, so elusive it can hardly be detected, is found to be so remarkable.

Ya. B. Zeldovich and B. M. Khlopov wrote a long article marking the 50th anniversary of the discovery of the neutrino by Wolfgang Pauli. The article was published in the Soviet journal *Advances in Physical Sciences.* Pauli discovered the neutrino as the result of calculations, or, as they say, "using only pencil and paper" (and began to blame himself for advancing a hypothesis that was impossible to check, in this he was wrong). In particular, Zeldovich and Khlopov write, with proper enthusiasm to suit the occasion, "Let us, in conclusion, pay homage to the hero of the day! In only half a century the neutrino has changed from an evasive entity into the foundation of our existence. A small mass has imparted supreme weight to the neutrino on the scale of the universe. A 'neutrino revolution' has occurred.... This has overturned our approach to physical phenomena. After centuries of domination of the principle of Occam's razor: 'Cut away all superfluous, and accept the simplest of theories of equal merit', we no longer fear its cold steel. All that is not forbidden can happen. And what is forbidden—may it not turn out to be allowed in the future, in view of new data?"

You can see how emancipated physicists felt themselves upon the discovery of mass of a particle regarded for almost half a century as having none.

We sense here, in the words of Zeldovich and Khlopov, that capacity to rejoice in new knowledge that induced Democritus of Abdera to declare that he would prefer to establish a single new causal relationship rather than occupy the throne of the Persian king.

We do not part yet with the neutrino. The reason is that it was discussed to no small extent in a recent International Congress devoted to the ocean. No, not Dirac's Ocean, but the quite terrestrial Pacific Ocean. This Congress was held in Khabarovsk in 1979. I was lucky; I attended the Congress.

A Physics Laboratory in the Ocean Depths

" 'What has the ocean got to do with this? We are dealing with the profound properties of matter. We are dealing with high-energy physics, the structure of distant stars and galaxies and, perhaps, the universe. What has the ocean got to do with this?' they ask us, physicists, working on the DUMAND project."

This is how M. A. Markov, member of the USSR Academy of Sciences, began his report at the plenary session of the Marine Sciences Committee of the XIV Pacific Ocean Scientific Congress. Then he went on to tell about the project, whose aim is to devise the largest physical instrument in the world by converting an immense volume in the ocean depth into a field of extrafine physical research.

The name of the project DUMAND is made up of the first letters of the words: Deep Underwater Muon and Neutrino Detector. A great deal has been written about the elusive neutrino, a particle for which practically no obstacles exist in our world. A neutrino, created in the centre of some ordinary star, instantly pierces its bulk and escapes into the vast space of the universe. A photon, for example, a particle of light, takes a million years, on an average, to travel from the centre of the sun to its surface, undergoing, during this time, many transformations. And this is not the end of its trials. After reaching the upper layers of the earth's atmosphere, the photon can "perish" in collisions with air particles in the very first five or ten layers of atoms.

But for the neutrino, not only the strata of the earth's atmosphere are no hindrance, neither is the earth itself. To be sure to catch a neutrino, you need a layer of lead with a thickness of about 3500 light years. True, this is the ideal condition for a hundred per cent effectiveness in hunting the neutrino. According to the laws of quantum mechanics, some tiny per cent, practically negligible of course, does nevertheless collide with protons and neutrons of terrestrial matter at much, much shorter distances. Specifically with protons and neutrons, because atomic nuclei, as a whole, are of open-work structure as far as the neutrino is concerned. It can pass between the particles of the nucleus without "taking notice" of them.

It was M. A. Markov that first reached the conclusion, over twenty years ago, that it is feasible under terrestrial conditions to register high-energy neutrinos. This problem was soon worked out in a diploma thesis under the guidance of Markov by I. M. Zheleznykh, a student at that time. On the basis of these theoretical investigations, the first devices for catching neutrinos were erected by Japanese and British physicists in India and by American physicists in South Africa. The neutrino traps were placed into deep mines that had been previously used for extracting precious metals. Under the guidance of A. E. Chudakov, the Institute of Nuclear Research of the USSR Academy of Sciences built the pilot plant of the Soviet neutrino installation in the town of Baksan in the Northern Caucasus. The installation is being further developed, although under very difficult conditions. These conditions have been specified by nature itself.

Our earth is continuously being bombarded by streams of particles travelling from distant parts of outer space. They are called cosmic rays. As far as our planet is concerned, the neutrino is only the least noticeable part of these rays. It proves more difficult to separate out the uncommonly rare collisions of neutrinos with matter of our planet on a background of violent and extremely frequent meetings of this matter with other particles than to hear somebody clap their hands during an artillery duel. Here is another comparison. We are required to throw a relatively fine-mesh net into a sea teeming with fish of various size, and to manage in some way to keep the large fish out of the net so that only the very smallest are caught.

Physicists have devised a method of solving this problem by making use of exactly this indifference of the neutrino to obstacles, the indifference that prevents them from being registered in some conventional way. The investigators arranged a wall of rock in the path of the cosmic rays. Then they went underground, behind a layer of soil that stops all other particles (except those having the highest energy), letting through the neutrino. The "big fish" are thus gotten rid of before they reach the fine-mesh net.

The volume of the chamber sunk into the earth is several hundred cubic metres, the registering surface of the chamber has an area of several hundred square metres. Signals indicating the collisions of neutrinos with protons and neutrons are to be received by this surface.

Such collisions are extremely rare. The Baksan Laboratory registers only dozens per year! But elementary particle physics is accustomed to investigate reactions that are observed millions and thousands of millions of times. This is the only way to clear up fine details in the course of these reactions.

In going underground the physicists in the Northern Caucasus left a layer of soil between the cosmic rays and their instruments that corresponds to six hundred metres of water. The ocean can provide us with a filtre several kilometres thick. The particles that are more active than the neutrino react with the water in this layer. Only the neutrinos (and other high-energy particles, the muons, also of great interest to the physicists) penetrate into the "chamber".

The idea of using the water of the ocean to catch neutrinos was also proposed by Markov as far back as 1960. It kept developing and, a little over ten years ago, American physicists advanced a project for an underwater detector or, more simply, a recorder of neutrinos. Its volume, according to the project, was planned to include a million cubic metres of water at the depth of five kilometres. Today, physicists have in mind a thousand million cubic metres of ocean, a whole cubic kilometre, weighing a thousand million metric tons.

How do they plan to convert a cubic kilometre of Pacific Ocean water into the operating unit of a physics laboratory?

The procedure is supposed to be somewhat like the following. First a superenergy neutrino, only one of many quadrillions of such, collides with a proton, the nucleus of a hydrogen atom or a particle in the nucleus of an oxygen atom. Created in the collision is an avalanche of new particles, which are much less elusive than the vanished neutrino. Their initial velocity is equal to that of light in vacuum. The velocity of light in water is slightly less, and the particles slow down, losing energy. This energy is evolved in the form of Cherenkov radiation, named after its discoverer, the Soviet physicist Pavel Alekseevich Cherenkov (also spelled Čerenkov).

Cherenkov radiation can be registered. This is done by installing instruments for detecting it in the water.

Each case of such radiation is to be caught by several traps; they are to note the path of the light beam, which is a continuation of the path of the neutrino that caused it. This means that we shall know the direction of the neutrino that ran into the trap. It is interesting when the neutrino has overcome four kilometres of water, entering the chamber from above. It is even more interesting if it enters the instrument from underneath, travelling upwards from the ocean bottom after having pierced our planet through and through. For instance, the Baksan Laboratory registered a neutrino that entered the earth somewhere in South America.

We shall be able to find out, at least approximately, what kind of particle arrived on earth, how much energy it carried; we shall be able to determine its path, from what part of the sky it came and what kind of cosmic source created it.

We shall learn formerly unknown features of the interaction of particles at such high energies. This may provide a key to the riddles of the structure of matter at the most profound levels of the microscopic world. It may disclose new mysteries of vacuum and provide a factual basis for constructing a unified theory of the universe's physical structure.

You already have a general idea of the outstanding role assigned to vacuum in the Weinberg-Salam theory. We have mentioned from time to time that certain propositions of this theory cannot as yet be either confirmed or disproved because the corresponding experiments require particles having gigantic energies, such that cannot be obtained by particle accelerators, at any rate, not in the next decades. Meanwhile, the existing accelerators are being called pyramids of the Nuclear Age because of their stupendous size and astounding cost. True, they are used to obtain particles with an energy measured in thousands of millions of electron volts. But for the experiments under discussion, particles carrying many trillions of electron volts are required. It may be that these are the kind that will be found among the neutrinos!

From the bottom of the ocean, from a depth of about five kilometres, a whole jungle of gigantic "seaweed" should stretch upwards. These are cables, each 1600 metres long. Hanging from them are light traps for detecting Cherenkov radiation, each about six metres in diameter. According to tentative data, there should be about 1260 vertical cables and about 23 thousand light traps. These traps, of fretwork design and hexagonal cross section, resemble still in the drawing stage a honeycomb, an ancient engineering invention of animate nature.

The vertical cables stretch from horizontal ones laid on the ocean bottom and connected to a laboratory built on the shore.

The idea of the light traps was proposed over two decades ago. In 1976, at a regular session in Hawaii, the Soviet physicists G. A. Askaryan and B. A. Dolgoshein and the American physicist Theodore Bowen submitted reports on still another technique for registering the collisions of neutrinos with protons and neutrons.

The avalanche of particles created by such collisions should heat water. Only about a millionth of a degree Centigrade, but in a negligible fraction of a second. In expanding upon being heated, the water emits a sound, somewhat like a click. This sound can be heard in water at a distance much greater than the glow from Cherenkov radiation can be seen.

It is proposed to supplement the chamber with hydrophones hanging from cables attached to floating buoys. They can be arranged comparatively far from one another; the design of a sound detector is much simpler than one for light and it costs less by a large factor. The use of hydrophones will enable the chamber to be expanded: in addition to the thousand millions of cubic metres of water containing detectors of both types, there should be ninety thousand millions of cubic metres of ocean equipped with hydrophones alone. Sound is to provide, perhaps less comprehensive, but still infinitely valuable information on neutrinos, and it will be obtained much more cheaply.

M. A. Markov, in his report, drew attention primarily to the high value of DUMAND for clearing up profound properties of matter. The American physicist John Learned dealt mainly with what information astrophysicists expect from DUMAND.

The superenergetic neutrinos arrive on the earth, not from the sun (it creates less powerful neutrinos), but from stars that have been transformed into the famous pulsars and black holes. They are created by events, still far from being clear to us, in the galactic nuclei, and by other processes involving monstrous energies.

The implementation of DUMAND is our only real way today to answer a question posed a long time ago, stated Learned: are there any stars and galaxies consisting of antimatter? Also existing besides the neutrino is the antineutrino, and the quantitative ratio of these particles in a stream of cosmic rays, emitted from a source of antimatter may be different than in a stream arriving from an "ordinary" cosmic source.

John Learned told about the specific efforts of American scientsts in developing the DUMAND project. They have already found a suitable location, in their opinion, for implementing the project. It is in the Pacific Ocean, in international waters, not far from the Hawaiian Islands. Here a depth of over five kilometres is found only sixty kilometres from the shore.

DUMAND is too enormous in scope to be handled by a single country. This is a unique opportunity, in the opinion of the American physicist, for international cooperation. Learned said that DUMAND can become the model for future, even more immense, international projects.

The sessions of the DUMAND Symposium were transferred in the last days of August to the shores of Lake Baikal. Here, A. E. Chudakov, associate member of the USSR Academy of Sciences, proposed that a model of DUMAND, one thousandth of its full size, be erected on the bottom of Lake Baikal. From the engineering point of view, such a task is facilitated by the fact that the lake freezes over in winter. The components of the structure can be lowered from the ice to the bottom of the lake at any required site. Baikal, of course, is not as deep as the ocean (the maximum depth is 1400 metres), but the first step is the hardest. The model of DUMAND should not be so very small at that: 100×100×100 metres, and a protective layer of water 1300 metres thick satisfies many of the conditions. Also being discussed is the feasibility of installing a similar model in one of the other lakes of the USSR. Nevertheless, these are specifically only models. Discussion of the fate of the full-size DUMAND continues.

Amazed by Our Own Achievements

Quantum physics is not only a young science, but a "green" one, still immature, according to the competent opinion of those engaged in it. Quantum physics has many troubles.

There are several schools in quantum physics, which, in many respects, do not agree with one another. Sometimes, in serious reports, they compare the situation in theoretical physics (as M. A. Markov did at a certain scientific conference) with an insane asylum, from the joke in which each inmate and each psychiatrist considers himself to be the genuine Napoleon Bonaparte and all the others to be imposters.

It should, incidentally, be pointed out that the discrepancies in the views and opinions of the physicists are considerable, but they have much, much more in common. The scale of their disagreement, so to say, in quantum physics is entirely different today than in ether theory at the turn of the century. The fact that physicists argue with one another is quite a natural phenomenon.

Those theories and experimental techniques, which even the physicists who proposed them regard as extremely far from perfection, still successfully explain the results of some experiments and predict the results of others. Of prime importance, very likely, is the following. Physically measurable effects that could positively contradict quantum theory are simply unknown today. Moreover, calculations following from theory coincide sufficiently often with experimental data with really fantastic precision. Quantum electrodynamics, for example, can predict the frequency shift in the spectrum of a hydrogen atom to an accuracy better than the fraction 10^{-9} (1/1,000,000,000). This is why quantum theory is called the most exact description of nature. At the same time, asserts M. A. Markov, "systems of equations of existing theory can be solved only approximately, and then with substantial reservations".

The situation is really astounding. Physics near the end of the 20th century appears to be the exact antithesis of the physics at the end of the 19th century. Then it seemed to be harmonious, universal, comprehensive and completed in all of its chief features. Today, theoretical physics is a "collection of separate fragments" (M. A. Markov), that is, scraps and pieces.

Paul Dirac once said that we can be absolutely sure that better times will come for physics. He said that such confidence is impressed on us by the very fact that the present difficulties of physics do exist.

Eighty years ago physicists were so satisfied with their science that they could see no future for it. One famed scientist stated at that time that "all the great discoveries have already been made". Today we see that "our physics" has many imperfections; physicists are unsatisfied with their theories, but how certainly they believe in their future.

The previous physics was surprised when something did not work out as expected; present-day physics is surprised that something always does seem to work out. The following quotations demonstrate the astonishment of our contemporaries at their own achievements.

M. A. Markov: "...the results of the calculations amazingly agree with the experimental data."

E. P. Wigner: "We are in a position similar to that of a man who was provided with a bunch of keys and who, having to open several doors in succession, always on the right key on the first or second trial."

It is truly a remarkable sight, unimaginable in past centuries: scientists feel surprise that their theories turn out to be valid, and their calculations are confirmed by experiments.

It may be that one of the reasons for such astonishment is the fact that scientists cannot get used to the nonvisualizability of their theories, to what is sometimes even called the tragedy of nonvisualizability.

Before we start to discuss this tragedy, we must come to an agreement on the definition of the very concept of "visualizability". It is most often understood to be the possibility of imagining a phenomenon or object in the form of a sensual image, that is, strictly speaking, the possibility of replacing it by a model that can be directly perceived by our sense organs. This condition was conformed to by a speck of dust for the atom in the case of the ancient Greeks and by a planetary system for the same atom in the case of Rutherford. But what about the model of the atom proposed by Bohr and Heisenberg, in which the energy of the electrons is radiated in only strictly measured portions and only when they jump from one orbit to another? Heisenberg's own opinion on this matter was: "Quantum theory deprived the atom of visualizable conceptions, perceptible to our sense organs and acquired in our everyday experience". No more visualizable (in the sense of the word as used by Heisenberg) are Einstein's curved space, and particles which at the same time are waves, and many other modern concepts.

The English writer Charles Percy Snow, who was at first a physicist and then became a writer, achieved, not too sensational, but quite tangible success in his first profession. In his book *The Search*, to some degree an autobiographical novel, he tells how this upheaval took place in the minds of physicists. Before they drew mental constructions of phenomena. These "pictures" (if only of atoms) became more and more confused and contradictory. The "artists" turned out to be unable to finish their works of "art". And then, writes Snow, they found a way out: "They will still be 'atoms'; but now we shall describe them in a definite mathematical way, instead of trying to make pictures with our senses in regions where the senses cannot enter."

Meanwhile, many generations of physicists had been brought up to believe that any phenomenon can be simulated mechanically, i.e. a model can be devised for it in the form of bodies (if necessary, travelling ones).

The shock caused by the fact that visualizable models could no longer explain new discoveries was really a tragedy for many physicists. Usually a tragedy in the past is of no more than historical interest to posterity. The shock endured by physicists has retained its initial keenness for many decades. New generations of physicists experience, in essence, the same feelings when they delve deeply into the problems of modern physics and cope with the works of the founding fathers of quantum mechanics and the theory of relativity.

> The greatest achievement of human genius is the fact that man can understand things which he already cannot imagine.
>
> *Lev Davidovich LANDAU*

Each tragedy has its victims. There are quite a number of people that turn out to be unable to be reconciled with the lack of visualizability of the microscopic world, and spend their time and efforts in desperate attempts to do away with the theory of relativity and quantum mechanics. In their stubbornness they resemble believers in the idea of perpetual motion machines.

To a considerable extent we can put the blame on this intolerable duality of our electrons and photons, protons and other particles. How much simpler it would be if a particle would always remain a particle. But no, we are obliged to take into account, in addition, the amazing fact that it is simultaneously a wave as well. Neither more nor less than simultaneously! We cite only a single, it would seem visualizable, example. You are looking at the sky at night. A photon of visible light emitted by a star arrives from an inconceivable distance to the pupil of our eye and enters the crystalline lens (neglecting the transformations that this photon could undergo in the earth's atmosphere). The lens manages to focus this photon on the proper point of the retina. In focussing, the lens was making use of the wave properties of the photon (a particle).

It is difficult, it seems, to conceive of a particle as being a wave. The opposite is also true. Leonid Isaakovich Mandelshtam, member of the USSR Academy of Sciences, was one of the world's greatest specialists in the field of oscillation theory, that is, of waves. He perceived the wave properties of quanta as something that is self-evident. It was somewhat more difficult for him to become accustomed to the fact that waves also possess corpuscular properties. Incidentally, the wave properties of particles, in the opinion of many scientists, have been better investigated, much more thoroughly, with conclusions checked to a greater degree by experiments and observations, than their corpuscular properties. The reason is that the wave properties were at first something new, posed more riddles, and riddles are what science has always been most interested in.

The new mathematical models, in place of the mechanical ones, are still withstanding the test of time. What about their lack of visualizability? Well, it must be admitted that it is an extraordinarily great inconvenience. There was a time when Einstein himself stated that only twelve people in all the world understood his theory. In a sense, this was the cost of its lack of visualizability. Nonvisualizability does not make a model incorrect, but visualizable models are more intelligible, easier to understand. Visualizability enables one to work more simply with a model, and evidently discloses more ways to its further development.

It is the same with a play: when you read it, it usually makes a much weaker impression on you than when you see it on the stage. A nonvisualizable model, such a comparison being permissible, is a play that cannot be staged in a theatre, that is, it cannot be expressed in real scenic form.

Plays, however, are written, as a rule, for the stage; nonvisualizable mathematical models of physical phenomena were and are devised by scientists with the stipulation that they cannot be conceived of in the form of sensual images. Does this mean that these plays will never be staged?

Today, we can, together with Heisenberg and quite a number of other great and famous physicists, consider the answer to be: yes. Nevertheless, I should like to believe that sometime in the future today's nonvisualizable models await at least partial dramatization.

There are various kinds of visualizability. There still are tribes in the world in whose language a number cannot be separated from the noun it qualifies. The cardinal number "two" cannot exist separately, but only in the combination "two fingers", etc. The Pythagoreans desperately made secrets of the "nonvisualizable" irrational numbers. Today, a line segment with a length of $\sqrt{2}$ is sufficiently visualizable for any geometer. The farther we go, the more we find! Previously, up to the end of the 19th century, only a mechanical model complied with the condition for visualizability. Now, an electromagnetic model is also considered suitable for that purpose. It may be that such a process of mastering newer and newer physical models by their visualizability will continue. To the extent, of course, that scientists will continue to devise newer and newer nonvisualizable models of newer and newer phenomena of the world. Such a proposal was advanced, incidentally, by the Soviet philosopher V. P. Bransky.

Evgeny Lvovich Feinberg, a Soviet physicist and associate member of the USSR Academy of Sciences, justly insists that visualizability is a historical concept; what was incomprehensible and nonvisualizable yesterday, becomes understandable and visualizable today.

Is it so long ago that the concept of the earth as a sphere and the sun as the centre of attraction of the planets became visualizable?

Nevertheless, it is possible that certain models will retain a lack of visualizability. Only it is necessary here to make a reservation. Philosophers and physicists of the Western world that see in this nonvisualizability evidence that the world is unknowable are in error. As we can see, models are nevertheless devised. They are devised and checked against their prototypes, revised as required and made to suit the phenomenon more closely. What is this if not cognition?

> Physics will change even more... If it is radical and unfamiliar...we think that the future will be only more radical and not less, only more strange and not more familiar, and that it will have its own new insights for the inquiring human spirit.
>
> *Julius Robert OPPENHEIMER* *

The language of the exact sciences is frequently said to be obscure and dry. It may sometimes be obscure from the viewpoint of those to whom this language is not

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* With these words of Oppenheimer, Abdus Salam concluded his Nobel Prize lecture in 1979.

intelligible at all or not always; but dry? The most poetic of historians and the most lyrical of poets can really sometimes either envy physicists, when they discuss their branch of science, or at least marvel at the brilliance of the images that the physicists resort to in their research. The subtlety and fancifulness of some terms they use can bring pleasure to the most whimsical of writers.

Strange particles have been brought into general use in high-energy physics, and *strangeness* has become a term designating one of the properties of elementary particle. Quarks, besides their other characteristics, have acquired *charm*. Physicists, as you know, have surrounded ordinary particles with *clouds* of virtual ones.

As an example, I cite below several comparisons and images, used by eminent physicists and concerning the problems dealt with in the present book.

One of the scientists likened a physical field (electromagnetic or any other kind) to a frying pan, with the temperature at each point of the frying pan corresponding, in the given case, to the field intensity.

The Hungarian physicist F. Karolyhazi proposes that we imagine that when two dinner plates are struck together, we obtain a saucer and two cups, instead of several broken pieces. This is exactly what may happen in the collision of two identical elementary particles: three other particles may be formed.

Ya. B. Zeldovich, member of the USSR Academy of Sciences, in beginning his article in *Advances in Physical Sciences* on the role of physical vacuum in cosmology, recalled an amusing incident that happened to Ivan Alekseevich Kablukov, then an associate member and later an honorary member of the Academy of Sciences. Kablukov was selling soda water flavoured with various syrups at a charity bazaar. He strictly complied with the instruction to ask: “What flavour of syrup do you wish?” When the purchaser wanted soda water without any syrup, Kablukov asked: “Without which syrup? Without raspberry or without cherry?” It may, most likely, be clear to you that Zeldovich, in this manner, was illustrating the proposition that in quantum physics a field exists even where there are no real particles.

Gerard t'Hooft of the Netherlands, in discussing theories inclined to unify interaction of various types, stated: "Hence, though physicists still cannot find the sole key to all known locks, it is, at least, known now that all the required keys can be made from a single kind of blank."

In his Nobel Prize lecture in 1979, Steve Weinberg said, "As theorists sometimes do, I fell in love with this idea. But as often happens in love affairs, at first I was rather confused about its implications."

Sheldon Lee Glashow entitled his Nobel Prize lecture as follows: "Toward a Unified Theory: Threads in a Tapestry". To explain this title, he likened the collective work of physicists to that of the makers of tapestries: "Tapestries are made by many artisans working together. The contributions of separate workers cannot be discerned in the completed work, and the loose and false threads have been covered over."

How closely do these images and representations correspond to the essence of the matter? It stands to reason that *charmed* particles do not have the charm that, according to even folklore traditions, is inherent in Parisian women. Neither are *strengenesses* of various kinds only a feature of particles whose definition includes the adjective "strange". Likewise, the idea of four keys made from a single kind of blank can hardly help to understand the main point of the attempts to construct a unified field theory.

Images, representations, analogies and comparisons are resorted to by scientists (and journalists) so that the senses of the readers or audience will aid their thinking processes. One can hardly expect images, representations, analogies, comparisons and even examples alone to provide complete understanding. Here we are obliged to recall the words of the Czechoslovakian mathematician Bernard Bolzano who asserted, at the beginning of the 19th century, that: "We do not regard examples and supplements as something that does damage to the perfection of a scientific statement. We only demand, but rigorously, that examples are never put forward in the place of proof...."

In scientific papers, examples are neighboured by proof, whereas in science writing, examples, against one's will, are frequently a substitute for proof.

How often modern physicists make use of such examples and representations to emphasize our lack of knowledge!

Towering theoretical physics of the end of the 19th century appears before us like a haughty and confident queen, dazzling and beautiful in her majestic maturity, as if all was known to her about the past, present and future. She does not suspect that by far not the whole world obeys the laws she has issued. Quantum physics of our time seems at times to be a youth, enthusiastically rejoicing at each new finding, amazed by his own luck.

This, however, is again only a comparison. It is followed by another: a comparison of ether and physical vacuum.

Somewhere in his voluminous science writing, Isaac Asimov asserted that a layman assumes science to be a method of discovering new truths, whereas science can only distinguish indisputable error from what may not be error.

What Ether and Vacuum Have in Common and Differ in

In what, in the final analysis, does physical vacuum, which has become firmly established in science, differ from "vanishing" ether? I decided to single out the "condensed answers" to this question into a separate section; to provide something like a summary to a considerable part of this book. Here, willy-nilly, it will be necessary to repeat something of what has already been discussed, but in incomparably more concise form.

Firstly, about what they have in common, about what unites vacuum and ether. Both are material media, obeying physical laws, interacting with ordinary matter and determining much in its properties and in the properties of space.

On this, with the exception of certain minor details, their likeness ends.

Now, about their principal differences.

Ether is primarily a fixed medium, and if it is mobile (as in certain versions), then only according to the rigorous laws of mechanics, like any well-known gas or liquid. This means that with such concepts of ether, we can always find an observer for whom the ether is fixed and can therefore be used as an absolute frame of reference. As to vacuum, we cannot, in principle, determine whether we are at rest with respect to it or in motion.

Ether is homogeneous, simple in essence, it is the same and invariable throughout and always.

Vacuum is a system with an extraordinarily complex arrangement and has a great many subsystems. It can be in various states and is capable of varying upon changes in the conditions it is in.

Particles of ether are analogs of gas atoms. These particles resemble ordinary atoms but are many times smaller. They usually obeyed the same laws that were obeyed by the atoms of ordinary substances.

Particles in vacuum are analogs of elementary particles except that they exist for a negligibly short time in comparison to their real twins and are therefore "freed" from complying with the law of conservation of mass and energy.

Ether was invented to explain natural phenomena; to it were imparted properties and features by means of which it was possible to understand what was actually observed. In its nature this resembled the fitting of the solution of a problem to the answer which was known beforehand from observations.

The properties of physical vacuum have not been contrived; they have been deduced from the properties of matter, perceived by various branches of the physical sciences. The most up-to-date ideas about vacuum were conceived and developed in elaborating quantum mechanics as a natural consequence of its main principles.

Experiments aimed at discovering the "ether of the 19th century" were not successful.

A number of well-conducted experiments undoubtedly confirm the existence of "vacuum of virtual particles".

These, of course, are only the main points in the opposition of ether and vacuum.

As is evident, the differences are ones of principle. But they are so great that even the term "ether", as we have already mentioned, was banished from modern quantum mechanics, banished and replaced, notwithstanding the intercession of Einstein himself. The ancient Greek art of navigating ships—cybernetics—has become a science of the 20th century; Rutherford's discoveries did not drive the word "atom" back into the past. As to ether, we almost never hear the word used any more; even as an anesthetic it has been replaced long ago by more effective ones. And Pushkin's line: "At night Zephyrus streams etheral" reminds us, not of the ether of Descartes and Newton, of Fresnel and Maxwell, but of the very first Aether, divine "light air".

Quantum mechanics has made Einstein's space into physical vacuum, it has filled this space with a material medium, without quarrelling with the theory of relativity. Although, it must be said, the union of quantum physics and relativity theory can be considered to have yielded fruit really worthy of these two great allies only after the following has taken place. The problem of gravitation must be solved at the quantum level. Physics must, firstly, acquire the capability to quantize a gravitational field by breaking it down into portions, and, secondly, relate gravitational interaction to the other three in a unified field theory.

Nothing and Everything

Part of the Conversation the Author Had with D. A. Kirzhnits, Head of the Superconductivity Division of the Lebedev Institute of Physics, USSR Academy of Sciences

Question: "What, in your opinion, are tomorrow's problems that will face experimental physicists investigating the properties of vacuum?"

Dr. Kirzhnits: "Tomorrow, in such cases, is usually understood to be in the distant future. I think it is high time to discuss "this evening's" problems. Definite phenomena have been predicted that should occur in vacuum in the vicinity of superheavy nuclei. Such nuclei may be produced in the collision of a heavy ion and a heavy nucleus. The vacuum should begin to "boil", emitting positrons, and its structure should be revealed to a more extensive degree."

Question: "Which theoretical investigations do you think are most likely to implement new discoveries that shed light on the properties of vacuum?"

Dr. Kirzhnits: "I am convinced that whatever a physicist is working on today—solid state theory, elementary particle theory, unified field theory, atomic nuclear theory or cosmological problems—he is also engaged, directly or indirectly, in research on the properties of vacuum.

"The fact that vacuum was found to be a superconductor emphasizes once again that common features of matter are characteristic at greatly diverse levels of its structure.

"When superconductivity was discovered, scientists were sure it was a phenomenon that would become exceptionally important in the system of our knowledge about nature. The first thing they thought of, of course, was how to raise the temperature at which superconductivity was still possible. In this matter, science and engineering have achieved appreciable success. Nevertheless, in the beginning many physicists were of the opinion that this fundamentally significant phenomenon could take place in only a comparatively narrow region of physical processes.

"Actually, however, it was found that the phenomenon of superconductivity is not simply one of many effects that solid-state physics was and is investigating. This most outstanding phenomenon, in which the quantum laws are manifested on a macroscopic scale, has revealed a great variety of phenomena of the same nature and has cleared up for science a number of things that are far, on the face of it, from what we call superconductivity.

"The most important ideas of superconductivity theory, whose founding required several decades, turned out to be equally applicable in solid-state physics, atomic nuclear theory and elementary-particle physics.

"What impresses me most in up-to-date physics is the fact that our world is found to be built, in general, according to the type-design principle, and if not of type-design elements, then at least according to 'type' designs. The same phenomena play a fundamentally important and similar role at various levels in the structure of matter.

"Hence, various branches of physics that describe this 'type-design' world become positively closer to one another. This convergence should and will continue. The cooperation of these branches signifies that we are close to the establishment of a unified pattern of the world...."

Question: 'Some physicists, those having nothing to do with superconductivity or elementary-particle theory, think that in the near future vacuum research is exactly what will provide a vital breakthrough in our knowledge of nature."

Dr. Kirzhnits: "Possibly. But even though today we are discussing vacuum in particular, it is, nevertheless, only one of the applications of new physical conceptions, including the role of superconductivity in nature. The cooperation of various branches of physics has given new strength to science. In the sixties quantum field theory underwent a crisis. A well-known Soviet physicist said that its principal method was a corpse that should be buried, although with all the honours that it deserved. Today this theory has firmly advanced. What is happening today to this theory and that of elementary particles can truly be called a revolution. And since physics is becoming more and more unified, this revolution should cover all of physics. The role of vacuum for physics cannot be overstated."

Question: "Thus, it may be that your neighbours in science, like your neighbours where you live, are more aware of what is happening in somebody else's family than in their own."

Dr. Kirzhnits: "Maybe. But more important is the fact that in the new, present-day physics there are no plain neighbours. All scientists, whatever their field, turn out to be relatives."

Beyond the Sea of Dirac or Everything Is Nothing

We now divide, quite crudely, the universe into three levels: the mega-, macro- and microscopic worlds. The microscopic world has its depths which, so far, do not lend themselves to experimental investigations. Only thought is capable of penetrating far beyond the depth limit of 10^{-15} cm. But it may be that many properties of matter are determined by the nature of events that take place in volumes of space of considerably smaller size. Quite a number of interesting ideas have been advanced in this line. At the present time, however, it is still extremely difficult to describe these ideas even by means of mathematics, not to mention experimental confirmation. Thus we now are entering the branch of physics in which we can sooner speak of guesses that are bold, sometimes even desperately bold, but, in the majority of cases, very far from being elevated to the rank of theories.

The American physicist John Archibald Wheeler is an outstanding scientist. Connected with his name, for instance, as well as with the names of the Danish physicist Niels Bohr and the Soviet physicist Yakov Frenkel, are the proposal and development of the liquid-drop model of the atomic nucleus. In the last decades, Wheeler has suggested some ideas with which the majority of physicists do not fully agree, but, nevertheless, admit that they are of great interest. Incidentally, if the viability of hypotheses depended upon the literary style used in expounding them, Wheeler, among physicists of the Western world, ought to be recognised as the greatest discoverer of new truths.

Wheeler has spent many years in advocating the idea that all of space should be considered to be empty. He has been making every effort to prove that, strictly speaking, there is nothing in the world, there never has been anything and never will be anything except absolute vacuum. He contends that the physics of the world is fully determined by its geometry, that the physical content of the universe is, in a sense, determined by the geometric shape of space.

In his time, Einstein, in developing the general theory of relativity, related gravitation with the geometry of space. According to Wheeler, "Einstein, above his work and writings, held a long term vision: There is nothing in the world except curved empty space. Geometry bent one way here described gravitation. Rippled another way somewhere else it manifests all the quantities of an electromagnetic wave. Excited at still another place, the magic material that is space shows itself as a particle. There is nothing that is foreign and 'physical' immersed in space. Everything that is, is constructed out of geometry." Einstein's long-standing dream, unrealized throughout his lifetime and to whose realization we are no closer today, can be expressed by the ancient saying: "Everything is nothing".

The picture of the geometric primordial entity of the universe proposed by Wheeler excites the imaginations of his readers.

Wheeler considers geometry to be the building material of nature. Any elementary particle, according to Wheeler, is "not a foreign and physical entity moving about within the geometry of space, but a quantum state of excitation of that geometry itself; as unimportant for the physics of the vacuum as a cloud is unimportant for the physics of the sky."

Indeed! But this statement, very likely, was made in a moment of ardent enthusiasm. Because Wheeler intends, nevertheless, not to ignore the physics of "unimportant" particles, but to explain it. This explanation is based on how space itself is organised, i.e. its purely geometric structure.

To comprehend, at least in some manner, on what Wheeler's ideas are based, it is necessary to penetrate into the "depth" of matter, deeper than to the atom, atomic nucleus or elementary particle. Wheeler contends that the scale of measurement becomes a quantity of the order of 10^{-33} cm. It is precisely of cells of this size that space is built at its deepest level.

What is the origin of this quantity? Max Planck, whose supreme achievement was the discovery of the "quantum of action", the minimum possible portion of energy in our universe, introduced the hypothetic concept of a "fundamental length". Distances shorter than this length, it is assumed, are simply impossible in our world, in exactly the same way that there can be no portion of energy less than a quantum of action. It is very typical, as a matter of fact, for quantum mechanics to strive to have space and time obey the same laws that govern elementary particles.

Still far in the future is the time when it will be possible to test the hypothesis of a fundamental length. But this should not and cannot stop theoretical investigations. It is worthy to recall that certain fundamental laws of quantum mechanics were discovered at a time when only a single particle—the electron—had been strictly and accurately discovered in experiments.

A thought experiment is frequently ahead of a real one, although in the final analysis it requires confirmation by actual experimental research.

Thus, a region of space with the characteristic distance of 10^{-33} centimetre, is, according to Wheeler "superspace". How does it look? Wheeler called it vacuum foam. Something bubbling, continuously changing shape. He writes: "The space of quantum geometrodynamics can be compared to a carpet of foam spread over a slowly undulating landscape. The continual microscopic changes in the carpet of foam as new bubbles appear and old ones disappear symbolize the quantum fluctuations in the geometry." "In other words," adds Wheeler, "geometry in submicroscopic scales, 'resonates' between one foamlike structure and another."

This conclusion, in his opinion, is inevitably reached by the consistent application of the quantum principle.

Here we find ourselves in a world reduced in scale even with respect to our "customary" microscopic world by a factor of about twenty. It is assumed that the diameter of the proton is approximately 10^{-13} centimetre.

The diameter of the earth is somewhat over 12 thousand kilometres. We shall write it as 10^9 centimetres (for the sake of simplicity, we sacrifice some accuracy, but in the case of elementary particles, the accuracy is still lower). With this approach, the earth is greater "in length" than the proton by a factor of 10^{22}, and the proton is 10^{20} times greater than the fundamental length, the measuring device for scales in Wheeler's vacuum.

From a man's height (let us assume it to be 2×10^2 centimetres, or almost 6 feet 7 inches, which is quite high, even for basketball players), only less by a factor of 10^7 than the diameter of our planet, you cannot see the distribution of oceans and continents. But this does not imply that they cease to exist. Hence, should it surprise us that even less commensurable virtual particles with their minimal cells are unnoticeable in superspace?

I repeat that Wheeler's ideas are insufficiently convincing. The images and analogies that he employs are filled with emotional, I would even say, artistic compulsion. He compares, for instance, superspace with the ocean. From a plane at a great altitude, even the roughest sea may look smooth and even. But a man in a small boat, tossed up and overwhelmed by the waves, is quite sure that he is not rowing along an even, mirror-like surface. If in such a situation the man has the courage to closely observe the foamy and churning water, he will witness this continuously changing complicated picture in its finest details and minute features.

The varying geometry of superspace is comparable to the surface of a real ocean observed by us from different distances and at various altitudes.

It is unfortunate, however, that an artistic image, no matter how convincing or persuasive it may be, is no proof in science. Other proof, so far, is clearly insufficient. But Wheeler backs his belief in superspace by one of the aphorisms that he is a past master in coining: "Moreover, the whole character of physics speaks for the theme that 'everything that can happen will happen'." But, on the other hand, he recalls, whenever necessary, that he has only proposed a hypothesis. Not without reason is the statement: "...only physics in the region of 10^{-33} cm can enable us to understand the physics of elementary particles", preceded by the cautious words: "It may well be that."

Also to be taken into account is that even if the picture of vacuum drawn by Wheeler turns out to be correct, the image of the stormy ocean he uses should not be taken too literally. An elementary particle in a vacuum, even in a "modern" vacuum of virtual particles, definitely does not resemble a boat rowed by a courageous observer. The waves can put the boat off its course or even overturn it. The direction of a particle travelling in a vacuum is constant. Photons, travelling from the earth to distant stars keep on their courses for millions and thousands of millions of years.

> **One must have faith that the incomprehensible can be cleared up, otherwise he will not ponder over it.**
>
> *Johann Wolfgang von GOETHE*

Thus, according to Wheeler, laws based on geometry and governing the ocean of superspace, specify the laws of the microscopic world that we are accustomed to. These latter laws are complied with by elementary particles and the Diras Sea itself.

The Soviet scientist K. P. Stanyukovich, D.Sc. (Phys.-Math), also proposed a hypothesis on the structure of vacuum at an ultradeep level. In certain aspects, it is quite close to Dr. Wheeler's hypothesis.

The centre of attention in Stanyukovich's hypothesis is also in the region of distances 10^{-33} centimetre long. His region, however, is not filled with vacuum foam, but with special particles whose feasibility of existence is derived on the basis of world constants. The size of these particles are exactly of the order of 10^{-33} centimetre, their mass is 10^{-5} gram. Their volume is so negligible that the density of the particles, with such small mass, is monstrous: 10^{95} g/cm^3. (The existence of such particles was independently proposed by M. A. Markov. He called them maximons, because, in his opinion, they were supposed to have the greatest mass of any elementary particles. Stanyukovich named them planckeons in honour of Max Planck.)

In Stanyukovich's hypothesis, as in Wheeler's, fluctuations of the vacuum, but having primarily a physical nature rather than a purely geometric one, play an extremely important role in the universe.

The following, for example, is how the beginning of existence of the metagalaxy was treated, according to Stanyukovich's cosmological model, in a book for the layman, called *Force That Moves the Worlds.* Stanyukovich wrote this book together with M. Vasilev and N. Klimantovich. They wrote: "Imagine an ocean containing an immense number of air bubbles. But this ocean has no water; it is an ocean of emptiness, matter also being absent in the traditional sense....

"That is, our ocean is an absolute void, a gravitational vacuum. Each bubble in it is a planckeon."

Further on the authors of the book write: "By further developing Wheeler's ideas, an entirely new point of view on the structure of elementary particles can be proposed.... If we assume that the size of the planckeon is 10^{-33} cm, then one cubic centimetre can hold approximately 10^{99} planckeons, and in the whole universe, 10^{180}.... The size of an elementary particle is 10^{-13} cm and its volume is 10^{-39} cm^3. Consequently, one elementary particle contains 10^{60} planckeons. Each one of them, in 'opening up' luminesces about 10^{-80} of its energy. This is what determined the energy (mass) of a single particle."

But this, of course, is only a hypothesis. Note how from various sides physicists approach with their proposals to vacuum. They carefully (and sometimes not very carefully) try various approaches to devise a new concept of the world, based on the idea of the special and extraordinary role of a physical vacuum.

It is meaningless to guess which of these approaches will turn out to be the correct one. Probably, many tentative brush strokes will be rubbed off this picture of the development of science. Others will remain and will blend some day with thousands of others, not yet made, into a single whole.

Such a single whole will also be incomplete. The road to absolute truth is an infinite one. This, by the way, is a guarantee that science will be conserved. Eugene Paul Wigner once noted that if we were completely informed of all the events in the world, everywhere and throughout all time, there would be no benefit from the laws of physics, and actually any other science.

It is worthy now to give at least one specific example of the further development of the ideas concerning the concept of a fundamental length and the special properties of space "near it". "Gravitational vacuum" is the name given by V. G. Krechet and V. N. Ponomarev to vacuum at such a deep "level of detail" in a paper published in a collection of papers called *Current Problems in Theoretical Physics*. Their paper is called "Problems of Gravitational Collapse, Neutrino Dynamics and Vacuum Power Engineering".

Before going any farther I point out that the term "vacuum power engineering" in the name of the paper does not imply that in the very near future vacuum is to be employed to advance engineering progress. Krechet and Ponomarev discuss the opportunities concealed in the vacuum foam mentioned by Dr. Wheeler. This foam, a gravitational vacuum, according to Krechet and Ponomarev, represents the great diversity of Stanyukovich planckeons.

The paper contends that fluctuations of vacuum constitute a store of vast energy. The readers are reminded that in the equations given in the paper for calculating the energy, the dimensions of the vacuum cells in which fluctuations occur are in the denominator and, moreover, they are in the denominator in the fourth power! At the same time, the amplitude of the vibrations of the gravitational vacuum comprises an inconceivably minute fraction of a centimetre. When raised to a power a fraction is drastically reduced, and to divide any number by a fraction, as we know, is to multiply the number by the denominator of the fraction and then to divide by the numerator.

Since, in our case, the denominator represents a fantastically huge quantity, calculations lead to staggering results: the energy of vacuum fluctuations comes to 10^{80} grams per cubic centimetre.

Everything becomes clear by comparison, says the old proverb. And we too compare this figure with the one that characterizes the energy density of actually existing atomic nuclei (10^{14} grams per cubic centimetre). If we also take into account that throughout the metagalaxy, the only part of the universe we know of, there are only about 10^{80} particles, the figure estimated by Krechet and Ponomarev seems to be simply unbounded.

All of this immense concentration of energy, truly exceeding anything that can be imagined, is in the "bound state", does not leak outside, and is completely utilized in providing a gravitational coupling between neighbouring fluctuations. In order to maintain bonds with others of their kind energy is necessarily expended by heavenly bodies and molecules and even the strange formations that flourish deep within the Dirac Sea.

Structural units of vacuum so strongly hold "hands" with one another that they "bind themselves hand and foot".

But these "hands" can let go, and energy, according to the authors of the paper, can escape from the vacuum under the condition that an outside force interferes with the "internal affairs of vacuum". This must be a huge force. As calculated by Krechet and Ponomarev, the energy density applied to the vacuum to obtain such an outburst should be comparable, in some degree, to the energy density in the vacuum itself.

> Our language is wise: there is a great difference between the expressions "I am convinced" and "I have been convinced".
>
> *Karel ČAPEK*

Where can it be found, the process that can create such almost improbable power? It is known by astrophysicists, who call it gravitational collapse. A collapsing, imploding star emits so much energy that vacuum can answer by releasing its energy. What happens next? The vacuum fluctuations at the gravitational level may first increase their amplitude and then, gradually attenuating, return to their initial level. In this case, the star will not even become a "black hole", but will simply dissolve, wrote Wheeler, in vacuum foam and disappear.

But fluctuations can also accumulate energy, being transformed as a result into real particles, into observable matter; observable in the form of mighty space explosions.

The celestial collections of astrophysicists contain exhibits, cosmological sources of energy, whose power is not readily explained within the scope of processes that we know about so far (although, in the opinion of many scientists, they can be explained). Based specifically on this circumstance is the hypothesis proposed by V. A. Ambartsumyan, member of the USSR Academy of Sciences, on the ultradense prestellar matter that provides energy for phenomena of this type. Krechet and Ponomarev believe that the emergence of vacuum energy can explain the most tremendous space explosions.

They do not, however, visualize the process as finding its completion in such an explosion. Vacuum, along which such a monstrous perturbation once propagated, retains a memory of this incident; the structure of the vacuum carries a trace of the past event. If another collapse, of still another star, occurs in the vicinity (on a cosmological scale, of course), the new vacuum perturbation will most probably be propagated along the old trace, that Dr. Wheeler calls a "wormhole". A "wormhole" becomes a continuous-operation channel for the transmission of energy between parts of outer space. It links the Galaxy, a transmitter of energy with, for instance, a quasar receiving the energy. As a result the quasar grows, loses its intactness, breaks up into separate stars and finally is converted in no more and no less than a young galaxy with an active nucleus that vigorously emits energy.

In the course of time, this galaxy, with its own collapsing stars, can become a source of energy for new cosmological centres of powerful emission.

Thus galaxies multiply on the nourishing soil of vacuum. . . .

Matter created by the energy of vacuum continues to increase in amount; the total mass of matter in the universe grows and grows; the all-penetrating gravitational field becomes stronger and stronger. The expansion of the Metagalaxy is being restrained to a greater and greater degree by this field. The galaxies withdraw from one another at a lower and lower velocity. This is to continue until the force of gravity decisively overcomes the inertia with which the galaxies are flying apart, converts expansion into compression. In the final analysis, compression will lead to gravitational collapse of the Metagalaxy. The energy of this collapse will again lead to perturbation of the vacuum, awakening its forces, and a new cycle of events will begin. This interesting version of a pulsating, alternatively expanding and contracting, world was proposed by Krechet and Ponomarev.

A description of this proposition, connecting the deep energy of vacuum with the general course of evolution of the universe and certain "particulars" such as stellar collapse, is properly fitting in the book *Something Called Nothing*. But we must remember, as do the proposers of the hypothesis, that it is very, very far in this case from the proposal to experimental proof.

Krechet and Ponomarev are making an attempt to find at least some possibility of carrying out observations that could confirm the validity of their ideas or bury them with due honours. Therefore, in the name of their paper, between gravitational collapse and vacuum power engineering, they inserted "neutrino dynamics". The authors hope that the highly penetrating neutrino may be able to provide them with information on the most ancient and most exotic events in the universe. The neutrinos are in a position to provide such information only if we are capable of taking it from them. It is insufficient to simply catch neutrinos, as we are doing at present; it is necessary to devise methods for finding out more about them when they have been caught.

I underline again that in the chapter called "Beyond the Sea of Dirac", I deal with assumptions and guesses, very interesting at times, but not with things that are rigorously proved. The very idea of the immense energy contained in vacuum seems to many physicists, not only unprovable today, but entirely wrong. D. A. Kirzhnits states, "The universe would look quite different if vacuum was a reservoir of immense (not to say infinite) energy...." Ya. B. Zeldovich emphasizes that "if vacuum had high energy, the nature of expansion of the Metagalaxy would be entirely different from what is actually observed. Consequently, only negligibly small values of the density of this energy are permissible."

Canvas and Paints

It is doubtful whether the physical universe has changed to any appreciable extent in the last several thousand years. But how different it has become for mankind in even the last decades!

To be more exact: our picture of the world has changed.

Man has always—ever since he evolved into Homo sapiens—had some concept of the world around him.

A flat circular disc in the midst of the ocean; such is the earth. Above, there are seven hemispherical crystal heavens to which the stars are fixed. Below there are three whales: "on those whales the earth stands.... One whale starts to move, and the earth rocks. When they all move at once, everything falls down into Tartarus." (The aforesaid is from the notes of an ancient Russian ethnographer.)

Another version is a tree whose roots are in the underground kingdom, whose branches are in the heavens, and whose trunk supports the earth.

Many such myths have come down to us from antiquity! For millennia Man has had the need to know, not only his home and street and village, but to conceive in his mind what we call by that most comprehensive word: the Universe.

Alas, too little did people know then of the world and of themselves for the pictures drawn by their imagination to have any resemblance whatsoever to the originals, since the pictures had been drawn by mythology and religion. Nevertheless, perceptible sometimes even through the "divinely inspired" texts are the persistently seeking thoughts of men who cannot yet do without a god, but who manage to supply Him with building materials and try to find "rhyme or reason" in divine creation. From the Book of the Old Testament called the *Wisdom of Solomon* we find that God with His "all powerful hand' 'had "created the world out of formless matter" and that He had "arranged all things by measure and number and weight."

> It must be so; for miracles are ceased;
> And therefore we must need admit the means.
> How things are perfected.
>
> *William SHAKESPEARE*

When—several thousand years back—the blows of continuously developing logical thought began to shake loose the tree of the world, when the whales began to swim apart and the first cracks appeared in the crystal firmaments of the heavens, the task of giving mankind a conception of the world, of drawing mankind a picture of this world, became the duty of science, still in its infancy. The first to undertake this job were the philosophers of both Occidental and Oriental antiquity. They were able to perceive features of the universe that have not changed down to our present-day concepts, even after so many centuries of development in human thought. They clarified the variability of the world and the struggle in it of opposing principles, and guessed that those finest particles of matter, which they called atoms, do exist. Still, it was impossible to derive from these brilliant guesses about the most general features of the universe, a reliable, orderly, logically sound conception of its most profound structure.

Ancient philosophers (here I make use of a metaphor suggested by the very words: "picture of the world") only prepared the canvas on which a scientific picture of the world was later to be painted; they made the first brush strokes on the canvas. When, later? After several thousand years. Natural science of modern times began to paint this comprehensive, broad picture of the world. In the 17th century, owing to the efforts of Galileo, Descartes and later Newton (as well as dozens of other scientists), physics became a genuine science equipped with mathematics. Since the most advanced branch of physics was mechanics, the picture of the world painted by the physicists and philosophers of those days was a mechanistic one.

The system of scientific conceptions of the world becomes more complete with each new scientific discovery. The picture of the world becomes more and more harmonious and perfect. But then—then it turns out that not all the new discoveries can be arranged within its framework, that not all of the brush strokes have been properly applied, that the nature of the universe is different from what we had conceived, it would seem, only a short time ago.

Our picture is replaced by a newer one. This is what is sometimes called a Revolution in Science.

Each picture of the world retains from its predecessors all the best, most important elements that comply with the objective structure of the universe.

Max Planck, who with his works initiated the quantum revolution in physics, noted at the turn of the century: "...even today's picture of the world includes certain features that can never again be effaced, neither by any possible revolution in nature nor by one in the world of human thought."

According to Planck, the "development of a unified and invariable picture of the world is the aim that science strives for".

For the time being, however, history is particularly demonstrating to us changes in the "drawings of the universe". This occurs even though very many scientists had the illusion, during the last three or four centuries, that what had already been discovered comprises, when taken all together, truth in its final instance. They contended that the final answers to the final questions had already been given or were just about to be given.

In the 18th and 19th centuries, the majestic edifice of classical mechanics was erected on the foundation of Newton's laws of motion and gravitation. The obvious power of these laws over the stars and planets turned the heads of astronomers. Comets, which had frightened the imaginations of superstitious rulers, as well as superstitious beggars, now appeared on days predicted by scientists. The earth itself "changed" its shape when it was found to be flattened at the poles; the family of planets began to grow....

How, under these circumstances, could the physicists in the field of mechanics keep from becoming excessively proud? For them absolutely everything in the world could find its explanation in the motion of bodies and the gravity between them. The Frenchman Pierre Simon Laplace, awarded the title of count by Napoleon and the title of marquis by Louis XVIII, reverently called Newton's law of universal gravitation simply: The Law of Nature. This law rules all in the world; it relates together, not only stars and planets, but molecules as well. The surface tension of liquids, the chemical interaction of substances, life itself are found to obey, within the scope of this picture of the world, the laws of mechanics (in the sense they were understood by Newton). Except, perhaps, that sometimes certain corrections were made in Newton's formula.

And when the famous French utopian socialist François Marie Charles Fourier founded his splendid doctrine that was impossible to bring about, he called the section setting forth its substantiation the theory of universal attraction of passions. He believed that this theory is based, as on a foundation, on Newton's law.

The well-known 20th century scientist John Desmond Bernal noted, in writing about Newton, that "Paradoxically, for all his desire to limit philosophy to its natural expression, the most immediate effect of Newton's ideas was in the economic and political field."

Indeed, Newton, and his followers were able to paint a successful picture of the world. This picture enabled one to obtain a very visualizable idea of the universe as a whole, or any part of it, any phenomenon or process.

The most amazing rule in the evolution of science is the fact that the more complete and perfect a theory seems to be, the more the reasons to consider it doomed to be revised, either as a whole or at least partly. Completeness leaves no room for including new discoveries within the framework of an incumbent theory, but discoveries are continually being made. The more new knowledge scientists of the 19th century discovered in the fields of heat, light, electricity, chemical reactions and many, many others, the more difficult it became to apply the laws of mechanics to the new discoveries, the more complex it was to construct a new mechanical model for them.

We already know how the mechanical models shirked when it was necessary to use them to represent the ether.

One of the knock-out blows was dealt to the mechanical picture of the world by Heinrich Rudolph Hertz, who discovered electromagnetic waves in 1888. Hertz determinedly freed the electromagnetic field (or, to be more exact, the concept of this field) from all traces of previous mechanical representation. Not only this branch of classical mechanics was forced to abandon its position. The scope of Newton's law was restricted to the force for which it was initially formulated: gravitation. At the turn of the century, the electromagnetic (sometimes called electrodynamic) picture of the world replaced the mechanical one, retaining, nevertheless, the "lines" and figures that were found to be indispensible.

The new picture of the world was more complicated than the old one had been. Previously, matter was supposed to consist of particles characterized by their masses; now the particles acquired a second most important characteristic: an electrical charge. From then on particles no longer travel in absolute emptiness or in an ether endowed with a complex set of properties. They travel now in a field, a second form of existence of matter, and their motion was found to be represented by the propagation of electromagnetic waves as well.

The laws of electromagnetism occupied, in the concepts of many physicists, the place that belonged to Newton's law in Laplace's time. They began to be perceived as being universal and principal in all fields and at all levels in the structure of matter. Attempts were made to derive the laws of mechanics from them. Several theories were proposed that contended that gravitation is also based on the electromagnetic properties of matter.

The immense work of several most prominent scientists, which was crowned by the advent of Einstein's theory of relativity, linked space and time together, and to matter. The theory of relativity became, in fact, the culmination of specifically the electromagnetic picture of the world. Not without reason was one of its postulates, the statement that the velocity of light (more exactly, of all electromagnetic waves) is restricted and absolute. Moreover, the first paper written by Einstein on the special theory of relativity was called: *On the Electrodynamics of Moving Bodies*. It is not by chance that the velocity of electromagnetic (light) waves is included in the famous formula $E=mc^2$.

For the sake of accuracy it is necessary to add that widespread recognition of the electrodynamic picture of the world came only at the end of the second and beginning of the third decade of our century. It was only then that courses including Maxwell's electromagnetic theory finally became required ones in the curriculum of physics students. And this was sixty years after it had been founded by the famed Englishman! Obviously, a considerable number of scientists were in no hurry to admit the fact that the previous physical picture of the world had been replaced by a new one.

This decisive victory, gained finally by electrodynamics, was, as usual in science, an omen of an early and even more decisive defeat, because new colours for a new picture of the world appeared at the beginning of the 20th century. It is usually called the quantum field picture. Sometimes it is simply called the quantum or the field picture of the world. Retaining the idea of the reality of a field, this picture reduced the two previous kinds of matter (particles and fields) to a single infinitely diverse one. It imparted wave properties to each particle, and the properties of a particle to each wave, thereby presenting a field as an assembly of such particle-waves.

What is the future of today's physical picture of the world?

In his book on the physical picture of the world, published in 1969, M. V. Mostepanenko makes the following prediction. Quantum field theories will continue to develop in the next two or three decades, and will finally include all particles known to us and their properties. This will signify the completion of the quantum picture of the world and, consequently, the beginning of its end, the beginning of a new picture of the world.

About one half of the time allotted by Mostepanenko for this process has already passed.

We see that this is indeed the truth. The last decade and a half have actually been a time of rapid development of elementary-particle models, a headlong linkup of all kinds of interaction in this world on a common basis (except that gravitation, even in hypotheses, lends itself with great difficulties to a unification with the three other interactions). It may be that a century from now they will speak of these attempts with the same slightly condescending wonder with which they write now of how, a century ago, gravitation was supposed to be due to electromagnetism. In a word, successes have been achieved. In the remaining years of the two or three decades foreseen by M. V. Mostepanenko, much more will surely be done. Thus, it may well be that Mostepanenko is soon to be congratulated for his successful prediction.

What is the picture of the world that will replace the present one? Here we are obliged to recall another forecast made almost twenty years ago.

Is Everything Vacuum?

An annual publication, consisting of a collection of papers devoted to (and not only to) relativity theory and called the *Einstein Papers* in Russian, has been published in the USSR since 1966.

The first issue included a paper written by G. I. Naan, a member of the Estonian Academy of Sciences.

To begin with, Naan made several remarks with a slight trace of irony on whether it is at all possible to make correct predictions of future discoveries. He referred to regrettable experience that demonstrates, as noted by the American astrophysicist Freeman John Dyson, the "incapability of the best of us to see just a little farther than the end of our own nose". But "notwithstanding and in spite of" the aforesaid, Naan nevertheless brought himself to make several predictions concerning future advances in physics.

Of especial interest to us here is the discussion of how the conceptions of science on the world as a physical whole are changing, and will continue to change.

Naan writes: "A result of the development of physics is the replacing of the picture of the world. The mechanical picture of the world was replaced by the electromagnetic one. The later was replaced by a picture that has no universally recognized name. It has been called, for instance, the relativistic quantum picture. In our opinion, it would be better to call the picture we now have, the field picture, because it is based on the concept that all is fields. It is difficult to say what picture will replace it. It seems highly probable to me that it will be the vacuum picture of the world."

You can imagine that it was very pleasant for me as the author of a book for the layman on the idea of emptiness to reread these lines only recently, about fifteen years after the collection of papers by G. I. Naan was published.

Any prediction, in any case in physics, is made so that it can subsequently be verified. Thus, to what extent have the past years justified assumptions published in 1966?

The picture of the world has not had sufficient time to undergo any radical change. For physicists, it is, as before, mainly the field and relativistic quantum one, constructed on the basis of conclusions following from relativity and quantum field theory. Quaintly combined in the widespread conceptions of physical reality held by lay-men are elements that come from the mechanical, electromagnetic and field pictures of the world.

This, incidentally, does not mean that the prediction has not come true. You could say, rather, that it is becoming justified. Because, in all these years the significance of vacuum has been slowly, gradually, but steadily enhanced as an explanation of the picture of the world, even though this picture has remained, for the time being, still a field one.

The triumph of the scientific classification of elementary particles has led to the construction of the first successful theories and hypotheses on the unification of the forces of nature, on what is common to them all, and with what their differences are associated. As you already know, there are grounds for expecting victory by an approach "from the side of vacuum".

The following is important, tangible evidence in favour of Naan's version. A book called *Gravitation* was written by Charles W. Misner, Kip S. Thorne and John A. Wheeler and published some years ago. It is a brilliant work, combining theory and experimental research, that enthusiastically gives an account, among other matters, of the finest, literally precision experiments that tested for (and confirmed) certain slight effects following from the general theory of relativity. Notwithstanding the natural rapture of the authors over gravitation, to which the book is mainly devoted, they write: "Of all the remarkable developments of physics since World War II, none is more impressive than the prediction and verification of the effects of the vacuum fluctuations in the electromagnetic field on the motion of the electron in the hydrogen atom."

So hihg does up-to-date science place this discovery, which we have already discussed and which is called in handbooks (I remind you) the Lamb shift of energy levels in the atom.

This phenomenon was discovered a long time ago, and predicted even earlier. The significance of vacuum fluctuations, by no means only those of an electromagnetic field, are perceived more profoundly as the years pass.

More and more scientific papers end approximately as follows: "Thus, taking quantum effects, the pair creation effect in particular, into account in processes associated with strong gravitational fields, is an absolute necessity for the solution of a great many problems of astrophysics and cosmology"; "Thus, it is impossible to solve the problem of the maximum number of nucleons in the atomic nucleus without taking vacuum effects into account"; "Thus, ..." A recent paper by Ya. B. Zeldovich in the Soviet journal *Advances in Physical Sciences* was called "Maybe Vacuum Theory Solves a Riddle of Cosmology".

The picture of the world became electromagnetic when, among other matters, the role of electromagnetic forces in the structure of the atom and molecule was perceived.

The field, being also the relativistic quantum, picture of the world was triumphant with the penetration of science into the atomic nucleus, with the discovery of laws governing elementary particles, and with the perception of the relation between space and gravitation, and of the nature of physical fields. As our investigation of vacuum proceeds, we see that it obviously plays an ever larger role in the field picture of the world.

Attempts were made almost three hundred years ago to explain the "attraction" of iron to a magnet by the law of universal gravitation. A hundred years ago, on the contrary, attemps were made to put Newton's law on a basis taken from electromagnetism theory. Today, many physicists, as you already know, perceive in gravitation and in electromagnetism, as well as in other natural forces, the result of processes occurring in vacuum, and the effects of properties that vacuum possesses.

Incidentally, on the face of it, there are not so many distinctly observed effects caused by the influence of virtual particles that could be brought to the attention of the theoreticians of experimental physics. We have already become acquainted with some of them. We repeat: the Lamb shift of the electron, the Casimir effect (the mutual attraction of two plates in vacuum), the anomalous charge of the electron and a few more. Are not these too few for the grandiose changes of our conceptions, not only of the microscopic world, but of the world as a whole in order for the physical picture of the world to become different? Hardly any facts, but what an immense building we are erecting on them! Let us recall, to be cautious, the words of Blokhintsev when he said that there are always sufficient facts, but not always enough imagination to interpret and unite them. A new theory may seem at first to be something like an inverted pyramid. A theory is frequently based, in its youth, on only one, two or three facts that do not fit in the mass of physical events, explainable in the previous way.

A certain—absolutely meagre—disorder in the motion of Mercury made astronomers fly into a rage at the turn of the century. It was the only one sufficiently convincing fact that contradicted Newton's law. This same fact was subsequently, for several years, the only one that confirmed the general theory of relativity. It required a good deal of time to check its predictions concerning the bending of a ray of light from a star when it passes near the sun and some other observable effects.

But it only seems that there are few facts in favour of a young theory. Also supporting it are the same facts that previously explained the old theory! The winning knight in a jousting tournament of the Middle Ages usually seized the horse and armour of his defeated foe. A young hypothesis, so to speak, even enters the battle on somebody else's horse: the facts on which the old theory was based. It only explains, "into the bargain", what was impossible to understand previously. Scientists would not give a wooden farthing for theoretical propositions that excellently explain the latest experimental discoveries but contradict long-known facts.

Moreover, the new theory quite soon begins to explain facts that have been known for a long time, but whose puzzling nature for the old theories nobody, for some reason, had paid attention to. We refer you to a simple example. If you sprinkle common salt into a fire, the flames will become yellow; this displays a special feature of the spectrum of sodium, which is a constituent of common salt. Spectral analysis, as a method of investigation was discovered in 1859, but the nature of spectra was made clear only by quantum mechanics, which was developed approximately half a century later. Its development had nothing to do with the problems of spectral analysis.

The theory of relativity won the contest with rival theories because the number of experiments or observations that confirm a theory is not of importance to science. Of importance is the number that contradicts a theory. Here an obstinate theory can cope with, not only ten or a hundred, but even a million exemplary, obliging facts. But even the tiniest cloudlet on the horizon may lead to a violent storm.

Vacuum theory is still very far from perfection. This may be why there are even no serious guesses yet as to which branches of physics can indicate the direction from which clouds, heralds of the storm, may arrive.

Formerly, European travellers were amazed to find that certain Papuan tribes of New Guinea had no special word meaning the colour green. This seemed the more strange because green was the predominant colour in the natural surroundings of these inhabitants of tropical forests. After some time both linguists and ethnographers came to the conclusion that exactly this last circumstance was responsible for the lack of such a necessary, it would seem, designation. Green was a constant and permanent background of their lives, whereas names are needed for the colours that stand out against this background.

Has not something similar to this happened to physical vacuum in the 20th century?

Science paid primary attention to events that took place on its eternal background. The background itself did not at first attract due attention.

Paul Dirac once said, in about the middle of our century, that the problem of accurately describing vacuum was, in his opinion, the main one facing physicists at that time. He concluded by saying that if, in fact, you cannot correctly describe vacuum, how can you expect to give a proper description of something much more complex?

You have already read, in any case in the present book, of the attempts to show that "all is nothing", dealing with elementary particles as fluctuations or excitations of vacuum, etc. But, even if we put hypotheses aside that are difficult to prove, we can be firmly sure of the immense contribution of vacuum in the real phenomena we observe. Thus the forest determines the way of life in the villages spread along under the canopy of its trees, even if the inhabitants have no word to call the colour of its foliage.

We shall not flatly contend after Wheeler that "All is Nothing"; we shall agree that Nothing in this case is Something, and that the Something has at least a most direct relation to All.

> For some concept to acquire the right to a preference over others that already exist in science, it must possess certain known qualities. It must explain and predict what is not explained and predicted by other concepts; it obliged, at any rate, to describe in a simpler and clearer way certain problems that were inadequately explained by previous concepts.
>
> *Aleksandr Mikhailovich BUTLEROV*

Only the future can show to what extent Naan's prediction can come about, and whether a time will come for recognizing the proposition that "Vacuum is everything and everything is vacuum".

But, evidently, it is already time for the up-to-date ideas on vacuum, at least in a first approximation, to become as necessary a part of the general culture of each person with a secondary education as the scientific ideas of the Copernican solar system or the atom of Rutherford and Bohr.

Now, after so many pages of a fervent hymn dedicated to physical vacuum, to the remarkable role it is already playing in the up-to-date picture of the world, after telling about the hypotheses that enhance this role, a few words of caution are in place. If not about the clouds that may appear some day on the horizon of vacuum theory, then the words may be about the wind that might be capable of driving them in over the horizon.

With the aid of properties inherent in physical vacuum, some of them being undoubtedly real and others presumable, up-to-date theories and hypotheses explain, or try to explain, a great many things, from the nature of all interactions to the mechanisms for bringing the metagalaxy to its present form. Physicists are linking vacuum, not simply with great, but with vast expectations. They see in vacuum the key to almost all the locks in the universe.

Are we not reminded of the situation with ether at the end of the 19th century?

Vacuum theory today is the beloved offspring of physics, its youngest child. Parents, as we know, are usually especially fond of their younger children because they have not yet become disappointed in them. Frequently, more is expected from beloved children than they are capable of. I allow myself to remind you that after the appearance of the general theory of relativity (which was then the youngest and best-loved daughter of physics), certain scientists, including the famed German mathematician David Hilbert, expected this theory to provide, in addition to other benefits, profound laws groverning the structure of matter, laws that control the electron and atom. Quite soon it became clear that such functions belonged to quantum mechanics, while "only" gravitation was left to the general theory of relativity. In the same way, possibly, the future will mark off a clear-cut boundary of the sphere of phenomena (even a most extensive one) to which the quantum theory of vacuum is applicable.

It is useless to even guess, of course, where this boundary will run; as yet we know too little about physical vacuum.

> That may be. I don't profess to be a scientific man, though I have heard somewhere that the science of one generation is usually the fallacy of the next.
>
> *Sir Arthur Conan DOYLE*

Indeed, it may be that vacuum theory will not become the "theory of All-and-Everything". This did not happen with the theories of Newton, Maxwell and Einstein, although such a fate was predicted for each of them when they were new. Nevertheless, these theories remain vital principles of modern physics. It is no small honour to be placed side by side with them.

Now, after these cautious words, sensible warnings and prudent stipulations, it is necessary to repeat: vacuum theory lays claim to a great deal more and, so far, no specific reasons are evident that belittle these claims.

"Today's rich and complex picture of vacuum is a logical consequence of experimental and theoretical research. This picture presents itself as an inevitable result of long, coordinated work of many scientists," wrote Ya. B. Zeldovich.

The concepts of emptiness and ether were, of course, also the result of long work of many scientists, but not coordinated work. Not without reason do the various versions of ether differ so drastically from one another.

Vacuum theory and the picture of the universe associated with it are destined to flourish and prosper in the coming decades. Even if the picture of the world does not become a vacuum one as a whole, the right of vacuum to an important place in this picture is indisputable, because in this matter people have sought out and discovered truth.

Hence, each of the consecutive pictures of the world contains some part of the truth, each of them is right in some respect, but it gives way to the next one, in which the share of truth is greater.

Here truth does not gain a victory over untruth, as in the struggle of science and religion; it conquers what is also true, but less profound and complete.

> A time will come when our descendants will be amazed that we had no knowledge of such obvious things.
>
> *Lucius Annaeus SENECA*

It would be interesting to attempt to imagine that picture of the world will some day replace the vacuum one....

Notes on the Margin of Our Picture of the World

Long, long ago somebody said that if the multiplication table had infringed upon human interests it would have been disputed.

The way the world looks affects both the interests of people and their feelings. This is so not only when a scientific picture conflicts with an unscientific one, when materialism opposes idealism and vice versa, but also in collisions in which each of the opposing sides consists of scientists.

Among physicists the highest honours are awarded to the one who promotes to the greatest extent a change in views on the very structure of the universe. Everlasting fame was brought to Newton by his law of universal gravitation, and not by his laws of mechanics, which were practically more valuable in his time and still are today.

Einstein was made the personification of the 20th century physics by his theory of relativity, and not by his work that served subsequently as the starting point for the invention of the laser. From the sixties, lasers, as we know, have initiated almost incredible advances in engineering, and not only in engineering.

This principle seems to be understandable: it is one thing to change something on the earth, a part of the whole, and quite another to change the views of people on the whole. It seems to me, however, that there is a psychological aspect of this mater that does not usually receive due attention. The concern of an intellectual person with what the world is actually like is not merely a matter of idle curiosity. He understands that he himself obeys the scientific laws of the world, he links the order of his own life with these laws and, to an even greater degree, he senses, feels and takes to heart these links.

"I do not think it unreasonable to hold the opinion that everything in the universe combines to cause every one of our actions, and this naturally includes all our opinions and desires; but whether an action, once performed, was inevitable from all eternity can only be decided when you have made up your mind whether or not the events are possible. . .which are not completely predetermined."

These words are from an autobiographical work by the English novelist and playwright William Somerset Maugham. Further on, the writer discusses the latest discoveries in physics (the latest at that time: the book *The Summing Up* was published in England in 1938). He came to the conclusion: "It looks as if chance must once more be reckoned with." But he immediately refutes this idea, because, as he writes: "It is well to remember that the two most eminent scientists of our day regard Heisenberg's principle with scepticism. Planck has stated his belief that further research will sweep away the anomaly, and Einstein has described the philosophical ideas that have been based upon it as 'literature'; I am afraid that this is only his civil way of calling them nonsense.... Schrödinger himself has stated that a final and comprehensive judgement on the matter is at present impossible."

Over forty years have passed since Maugham wrote these words. A great number of "final and comprehensive judgements" have been expressed during this time. But I think that neither of the two extreme points of view has won by a knockout; neither has gained a victory that could put an end to all arguments on the matter. A decision on points with a large advantage can be given, however, to the supporters of the opinion that the anomaly here is in no way a seeming one. Victory went to the point of view of those who consider the probability of the world to be a deep-seated principle, rather, so to speak, than something only on the surface of phenomena. Though there are, even at the present time, followers of Einstein's viewpoint on this problem. They hold that all that is random in the quantum world has its reasons, and that when we understand them all probability will vanish.

Of greatest interest, in my opinion, is not the fact that this English writer tensely kept up with the events of up-to-date science and took them to heart. Most important is that he tried to find whether the conclusions of science are directly compatible with his own life. The lines quoted above are preceded in the book by the words: "It has seemed to me that I have now and then been able to put forth an effort that was not wholly predetermined. If it was an illusion it was an illusion that had its own efficacy."

For thousands of years mankind has sensed its unity with the universe. We do not have in mind the primordial and primitive feeling of the inseparability of man from nature. Ancient philosophers spoke of man as a microcosmos, as a being that repeats in itself all of the universe, in epitome and image.

Again and again the sages of the Orient returned to this idea in the Middle Ages, as did the Scholastics of Europe. Surprising, perhaps, but they were evidently right about one matter. Is it not true that the mind of Man holds the whole world; does not our thought embrace the universe?

Here we are, burdened with quite terrestrial cares, worrying for some reason about the future of this same universe. We are troubled about the problem: is life on earth accidental? The whole vast regions of space turn out to be something like a garden plot of our earth, and the microscopic physical world, sometimes completely incomprehensible, is something like the soil of this plot.

Incidentally, the Stoic philosophers of ancient Greece and Rome, likened ethics, the study of morals, to the fruits of an orchard, whose soil is physics, a study of nature, and which is fenced in with logic. Needed for the sake of the fruit are both soil and a fence; without them we cannot harvest the ripe fruit.

Our vacuum in such a detailed analogy is the subsoil or, more exactly, the continental, primordial layer that supports the soil and all that is erected and grows on it.

The struggle of defenders of a world in which there are no chance events with the supporters of one in which chance is recognized is two and a half thousand years older than the controversy between Einstein and Bohr with Heisenberg. It would probably be quite interesting to clear up to what extent today the specific stand of a scientist on this specific (though very general) problem is affected by his personal unwillingness (predetermined by his upbringing and education, way of life, nature and temperament, etc.) to obey necessity or, on the contrary, chance. Also, what specific factor played the decisive role. Naturally, rigorous proofs will ultimately convince the most deep-rooted skeptic, if he is capable, of course, of understanding them.

But feeling can put up resistance, even when it is compelled to yield to reason. Hendrik Antoon Lorentz, the famed Dutch physicist and one of those whose work lies in the foundation of modern science, bitterly regretted that he had not died before the dethronement of classical physics. It was difficult for him to reconcile himself to this fact and, evidently, even more difficult to agree with the conclusions of those that demanded the overthrow.

Many attempts have been made, from way back, to classify men of science, to divide them into categories, in accordance with the most general principles of their work. The eminent German chemist Friedrich Wilhelm Ostwald, for instance, divided scientists into romanticists and classicists. The former, he contended, are generators of brilliant ideas. After proposing a remarkable hypothesis or making an epochal discovery, they usually cool down with regard to their own brainchild and no longer participate, or only to a limited extent, in its further development. Classicists, on the contrary, rarely make absolutely new proposals, but they are the ones that bring to logical completion, to the feasible limits of perfection, the initial ideas of romanticists and their own ideas.

This classification is quite arbitrary. Newton and Mendeleev, for instance, cannot be put into either class.

Now I shall try to attract your attention to another possible classification (though again arbitrary and incomplete) of scientists into types: according to their attitudes with respect to chance.

We have already seen, using Maugham as an example, how this problem affects a person appearing in the role, so to speak, of a consumer of scientific information. No less emotional, in any case, were the attitudes toward chance of almost all the founders of scientific theories concerning the correlation of chance and necessity in life and nature.

The first ancient philosophers put their world into strict order, establishing the first picture of this world that was scientific in its principles. They proclaimed Mighty Necessity the lord and ruler of the universe. The most clear-cut formulation of the principles on which this approach is based was by Democritus in the 5th century B.C. He asserted that everything in the world has a cause and takes place owing to necessity. Chance events only seem to be so because we do not know their causes. These were outstanding ideas in a world that had not long before, in the opinion of most people, obeyed the arbitrary rule of the gods on Mount Olympus. Thought had thus won a great victory over superstition.

Another ancient materialist was Epicurus. He developed the atomistic ideas of Democritus by adding a third parameter—weight—to the properties of Democritean atoms—shape and size. He had entirely different ideas about chance. He allotted atoms with the capacity to spontaneously and randomly deviate from their course. What an amazing guess, and how profound if we recall the laws of quantum mechanics discovered in the 20th century.

How did this great philosopher arrive at this wise guess? On what did he base his bold statement: "Necessity, introduced by certain people as a supreme sovereign, is non-existent; but some events happen by chance, whereas others depend upon our will."? Epicurus is guided—quite frankly—not by conclusions based on any observations, but only by his own flat refusal "to be a slave of fate as it is understood by the physicists". His feeling of independence is outraged, because it is a "misfortune to live in necessity". He himself admitted that his method of explanation has as its aim the nonchalance of self-consciousness, rather than the study of nature as such. The personal motives, lying here on the surface, do not, however, deprive the Epicurean approach of its scientific worth. His innovations in atomism became "the basis of a deeper view of the interrelation of necessity and chance", as we can read in a modern edition of the Dictionary of Philosophy. Epicurus was very successful in identifying himself with the universe.

Titus Lucretius Carus enthusiastically continued the work of Epicurus in his immortal poem *On the Nature of Things*:

> What keeps the mind from having inside itself
> Some such necessity in all its doings,
> What keeps it from being matter's conquered slave?
> The answer is that our free-will derives

From just that ever-so-slight atomic swerve
At no fixed time, at no fixed place whatever.

Marcus Tullius Cicero, the eminent Roman orator, philosopher and politician, had difficulty in finding sufficiently abusive words for followers of Epicurus and, moreover, for the philosopher himself, as if two hundred years had not passed since he died. Cicero asserted: "Yes, and the very deviation is an arbitrary fiction; he (Lucretius) says that the atom deviates without cause, but nothing is more shameful for physics than to maintain that one and another event occurs without cause..." (Einstein, as you recall, even if only from our quotation from Maugham, in a similar situation, called such ideas "literature". But this was Einstein who, in contrast to Cicero, did not like to offend his colleagues!)

Pierre Simon de Laplace carried Democritean mechanistic determinism to its extreme limits. He contended that all that happens in the world is uniquely determined by what has already happened in the past.

To be honest, it is easier to understand the horror of Epicurus when faced by necessity in the Democritean-Laplacian sense than the indignation of Einstein over the fact that the god (meaning nature) of Bohr and Heisenberg "plays dice with the world".

How close to so many of us is the follower of Epicurus that exclaimed: "Epicurus is our saviour; he granted us freedom."

And what would you expect? Chance in the behaviour of atoms in antiquity and "present-day" elementary particles turns out to be the problem of free will, which is something that has stirred the minds of people for thousands of years.

Do you recall with what the Jesuit reproached young Aramis in the *Three Musketeers* of Alexandre Dumas? "You are nearing," exclaimed the Jesuit, "that famous point of free will, which is a fatal reef. You are sailing dangerously close to the insinuations of the Pelagians and semi-Pelagians*". Evidently, it was indeed a temptation

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* Followers of Pelagius, a 4th-century British monk who denied the doctrine of original sin and maintained that man has freedom of will.

if Einstein became rude, Lorentz regretted that he had not died in time, and Heisenberg postponed the solution of the problem to the distant future.

Baron Georges Léopold Chrétien Frèderic Dagobert Cuvier, the eminent French naturalist and founder of comparative anatomy and paleontology, found a fortunate way out. He believed that there could be chance in nature, but that science should not take it into account and, consequently, there is no reason to think about it.

The world of especial probability in quantum physics has often provoked both direct resistance and simply strong dislike. I do not know whether these feelings were shared by the American S-F writer Robert Sheckley when he wrote his short novel *Mindswap*, but his "Twisted World" is, in some respects, an obvious and malicious parody on quantum mechanics. In the so-called "Musings of the Mathematician Edgar Hope Grief," quoted in Sheckley's book, we read the following.

"...For indeed, as we have seen, the Twisted World (sic) performs the work, both necessary and hateful, of rendering indeterminate all entities and processes, and thereby making the universe theoretically as well as practically ineluctable."

Further on we find: "A wise man once asked, 'What would happen if I could enter the Twisted World without preconceptions?' A final answer to his question is impossible; but we would hazard that he would have some preconceptions by the time he came out. Lack of opinion is not armor."

Dialectic materialism accepts both necessity and chance; the one and the other exist and, morevoer, are closely related, inseparable from each other. Each phenomenon occurs by virtue of internal necessity, but diverse are the conditions under which it appears, numerous are the factors that influence it, and all this is manifested in chance which accompanies the phenomena.

Due, to a great extent, to quantum physics, the concept of statistical laws is now part and parcel of science. In this concept the future is determined by the present not uniquely, but with a certain element of chance: not according to Democritus and not according to Epicurus.

Maugham interpreted this as the annihilation of causal relationships. Actually, our concept of causal relationships became more profound and extensive.

Human culture, based not only on thought, but on feelings as well, continues to remain readily noticeable even at the most abstract heights of theoretical reasoning.

Nevertheless.... We are accustomed to conceive heroes of the past as monolithic figures, holding a definite opinion on each question, at least after they had arrived at it through much distress. This is how, evidently, they appear in the present book. But what are they like in actual life? According to legend, Aristotle, proud in his knowledge of the world and having, evidently, some good reason, committed suicide because he could not explain what caused ocean tides. The Count and later Marquis Laplace, that in many books, including the present one, is pictured as a militant apologist of a strictly deterministic world, sometimes wrote in an entirely different key, doubting and even in despair.

People so frequently contradict, not only others, but themselves as well. They change their point of view, correct themselves, agree with others.... Evidently, there is no other way to get to know the universe, which is also full of contradictions.

On the Brink of Remarkable Discoveries

What promise are we offered by research on vacuum, if we pass from theory over to practice, and not just simple practice, but the everyday variety?

In the last two hundred years science has pampered mankind by the fact that it began to pay much too manifestly. Nicolas Léonard Sadi Carnot constructed his theoretical model of a heat engine and, quite soon, steam boilers began to operate with much higher efficiency. Heinrich Rudolph Hertz had only just discovered radio waves when the first radio transmitter was invented (seven years is only a short time). Einstein once described an interesting phenomenon that can occur with light (maybe only pure theory) and now, if you please, not many scientific laboratories, research centres, clinics and even whole branches of the national economy can get along without lasers.

What promise are we offered by theoretical and experimental research on vacuum?

Making predictions is a dangerous business. Mark Twain once said that all through its history mankind has been engaged in a funny game called: trick a prophet. Hence the author of the present book, out of sensible prudence (or, perhaps, out of shameful cowardice), decided to appeal to such experts in the field of forecasting as S-F writers.

Before me is a Russian novel written by Mikhail Yemtsev and Yeremei Parnov and called *The Sea of Dirac.* I am sure you now understand what its name means. The characters in the novel find that by transforming virtual particles under laboratory conditions into real particles, they can produce exact copies of any articles from vacuum. Making use of such an opportunity, granted to him accidentally, an unscrupulous employee of the research institute makes precious stones and gold articles. At the same time he produces money that has only one shortcoming: the coins and bank notes are too much alike. They are identical to a degree that cannot be achieved even by the mint.

The president of the Vacuum Physics Institute (in the novel) writes to a friend in another city, describing the scientific basis for vacuum copying. He writes that by "supplying a good vacuum with a sufficiently high concentration of energy, we shall be capable of transmuting the Dirac virtual background into a certain number of particles. Then, after investigating the kinetic laws of the process we would be able to set up the process itself. It promises fantastic prospects, because the resources of vacuum are truly unbounded. The source of matter of the given composition and quantity could, in principle, be any point in space. We need only to determine the qualitative and quantitative characteristics of the process and then. . .".

The two authors have devised, it seems to me, an excellent idea, and the novel itself is an interesting one.

But how does all this sound from the viewpoint of science?

There do not seem to be any objections in principle. We know that virtual particles actually can be transformed into real ones if we supply them with energy. Then, in some way we can unite the particles into atoms of, for example, gold, thereby forever solving the problem of its extraction. No geological prospecting, no mines, no labour-consuming operation for washing the gold-bearing rock are required. But objections in principle may here be replaced by objections of a strictly engineering or engineering and economical nature. I shall not here touch upon the problem of how the particles obtained from the virtual ones can feasibly (if at all) be collected together so that you could hold a piece of the gold in your hand. Science fiction has its own accepted rules. What I am getting at is the price of gold produced in such a manner; it will be an astronomical number. This is readily evident if you recall two quantities and a single formula. The formula is: $E = mc^2$. It follows from this famous formula that one gram of matter can be obtained only as the result of an enormous outlay of energy. The velocity of light $c = 300\,000$ km/s and one kilowatt-hour costs the user in the USSR 4 kopecks. I leave further calculations to the reader.

True, we would be sure to obtain, in addition to each gram of gold, a free gram of antigold into the bargain: particles are created "in pairs" with antiparticles. But, very likely, the storage of antigold will be even more expensive than its production.

So what? Does this mean that we shall not scoop matter out of the "Sea of Dirac"? As a possibility in principle, I repeat, it cannot be excluded. As to a practical one, we leave it for the time being to S-F writers. They have the right to transform virtual particles into gold ingots now, without waiting for better times. What would science fiction be worth without scientific fiction?

Doubt affords me no less pleasure than knowledge.

Michel Eyquem de MONTAIGNE

Another idea is to derive energy from vacuum. The majority of specialists in quantum field theory decidedly consider this to be absolutely impossible, and the arguments of this majority sound very convincingly. I take the liberty to repeat a slightly curtailed version of the statement made by D. A. Kirzhnits in a previous section. He said, "The universe would have a different appearance if vacuum was a reservoir of immense (not to say—infinite) energy. . .if there was high energy in vacuum, the nature of the expansion of the metagalaxy would be entirely different from what is actualy observed." I supplement this part of Kirzhnits's answer to the question of the energy of vacuum with the words (omitted in the previous quotation): "But, good or bad from the viewpoint of the energy crisis, it follows from many convincing theoretical investigations that the energy of vacuum is hardly nonzero. Vacuum, in many respects, is a riddle; much should be expected of it, but not all that we require."

Nevertheless, another Soviet physicist, V. G. Lapchinsky, thinks that it is feasible to obtain energy from vacuum.

I want neither to exclaim optimistically "suppose that it is" nor to sadly sigh over such an intriguing idea buried alive. How fine it could have been: take energy from one volume of vacuum and deliver it to another volume where, in exchange, we obtain matter! Alas, the probability of something like this happening is extremely small.

By the way, it was physicists, not S-F writers, that proposed the idea of using the polarization of vacuum in space to accelerate the motion of interstellar ships of directly deriving fuel from vacuum to drive the ships. True, the physicists advancing this idea almost immediately disproved, by subsequent calculations, the feasibility of its practical application even in the far future. One physicist noted in this connection: yes, of course, it looks entirely unreal, but if we imagine ourselves in the place of those who initiated the era of electricity, we must arrive at the conclusion that they surmounted the same barrier of unreality: in our world almost all bodies are electrically neutral.

This analogy, like any other, cannot serve as a proof, but it could well be the subject for discussion.

* * *

The problems of vacuum are tied into a single knot with all the most fundamental problems of physics as a whole. Normal progress of our 20th-century science is impossible without their consecutive solution.

Vacuum is a fundamental problem in itself, and such problems are investigated, as a rule, without worrying about their eventual practical benefit. Not meaning, however, that such benefit is not to be expected.

> Supreme truth is possessed by the cause of effects that, in their turn, are true.
>
> *ARISTOTLE*

Victor Weisskopf, who has previously been mentioned, decided once to estimate the expense to mankind of fundamental science. He only included research that deliberately did not pursue any practical purpose, striving only to discover new truths. He figured that in recent times the total expenditures on science are doubled every decade, then he took the approximate amount for the current year and set up an inverse geometric progression back into the past. He found that by 1971, when he cited the results of his calculations in one of his lectures, mankind had spent, from Archimedes to our days, about thirty thousand millions of dollars on fundamental "pure" science. This was equal to the twelve-day gross output of the USA in the prices of 1971.

This, of course, is not very much if we recall how much fundamental "pure" science has paid back from Archimedes up to our time. Discoveries that were made during the investigation of the most profound scientific problems are embodied in the things that surround us in our homes, in the machines and instruments we work at and in all that has become part and parcel of everyday life.

Sir Christopher Wren, the English architect who designed and built over sixty London houses and buildings, including St. Paul's Cathedral, was interred under the choir of this magnificent structure. His tomb has the following inscription: "Beneath is laid the builder of the church and city, who lived above ninety years, not for himself but for the public good. Reader, if thou seekest his monument, look around." The last sentence could be the epitaph of Archimedes, Galilei, Huygens, Newton, Lomonosov, Mendeleev, Einstein, Bohr, Tsiolkovsky, and many, many more.

Archimedes was not a shipbuilder, Tsiolkovsky did not build engines for his rockets. . . . Theoreticians were rarely engaged in the practical application of the conclusions from their fundamental research. Likewise, it is not necessary for an architect to lay bricks in his buildings.

It is an alluring prospect to expect from each new fundamental scientific work specific, purely practical consequences: new kinds of energy, new methods of space travel, new. . . . Continue the list yourself.

We return again to the question asked at the beginning of this section. Can we expect all of this from research on the problems of vacuum, even if not at present, but in the quite distant future?

In answer to the scepticism of many specialists it seems to be natural to recall that Rutherford and other founders of atomic theory ridiculed the fools that proposed utilization of the atom's energy.

A comparison, however, as we have had occasion to remind the reader several times, is no proof. Among scientific predictions (in contrast to political ones!), it is usually the unfulfilled ones that are remembered.

It remains for me to repeat words said by a physicist, not with respect to vacuum, but astonishingly appropriate in the given case: "Given our ignorance, it would be just as presumptuous to deny the feasibility of useful application as it would be irresponsible to guarantee such application."

Nevertheless, I shall allow myself to be irresponsible to some extent. Nowise guaranteeing a definite way to utilize vacuum, we can warrant, all the same, that research will be sure to lead, in some way, to specific practical benefit, here or there, in this or that branch of engineering.

Investigations should be conducted regardless of such benefit, just like a child should learn even if he is not given a candy bar for each excellent grade he earns. All of us are children of nature and we study in her school.

In the final analysis, according to Francis Bacon, Knowledge is Power. Our time has added to this old concise proposition a significant epithet, defining science as a productive force. The progress of an advanced society has always been associated with scientific knowledge, only never before has this been manifested with such convincing obviousness.

We are expecting new remarkable discoveries!

> Now the true and lawful goal of the science is none other than this: that human life be endowed with new discoveries and powers.
>
> *Francis BACON,*
> *1st Baron Verulam, Viscount St. Albans*

In Place of a Conclusion

Thus we end our short journey through centuries, decades and years. Together, in the light of newer and newer discoveries, we have followed the changes in the idea of a background of the universe, the setting upon which all the world's events occur.

We became acquainted with emptiness and then with ether that opposed this void. Finally, we found out something about physical vacuum. Both ether and physical vacuum can be put, with the appropriate reservations, into the category of "anti-emptiness". They both "emerged" for the purpose of replacing emptiness in our conceptions.

According to the laws of dialectics, the process of development passes through three stages of Hegel's triad: thesis, antithesis and synthesis (assertion, negation and, finally, negation of negation). This is what happened as well to the development of the idea of a universal material medium.

Aristotle introduced an omnipresent ether that permeates everything into the picture of the world he devised. Descartes, Newton, Huygens, and many others inserted a foundation, based on the scientific concepts of modern times under the idea of ether. They made use of ether in their hypotheses and theories.

This is the thesis, or assertion.

As a matter of fact, the drawing of the universe drafted by Newton could do just as well without any ether. This is evident from Newton's statements in the section called An Answer to all Problems under the heading of his first position. The picture of the universe associated with the theory of relativity has no need whatsoever for such a special material medium. This means that in the development of this idea one of Newton's positions and the proposition of relativity theory concerning this problem correspond to negation.

Finally, quantum mechanics created strictly scientific concepts of the real and exceptionally meaningful existence of a universal material medium.

Now we have reached negation of negation in the development of the idea.

In accompanying one of the remarkable scientific ideas in its journey through time, we did not expect, as you may recall, to find out the "whole truth" about the universe called the Vacuum, about the history of its discovery and its comprehension. A great many special problems, however, have remained untouched in our account, a great many facts and hypotheses were not even mentioned and a great many eminent scientists working in this field were not named here.... Hence, remember please that each scientific proposition, as well as each scientific assumption, dealt with in this book, is primarily a representative of others that were not mentioned.

This book began with an epigraph from Goethe. Almost immediately preceding the quotation, Mephistopheles asks Faust whether he can imagine "wastes and solitude" (which we interpret to signify "emptiness"). A modern physicist can answer, in the spirit of the next lines of Faust, that he can.

Or, maybe, we should repeat Faust's proud retort:

> I think that you might save yourself such chatter,
> Come, let us fathom it, whatever may befall,
> In this, thy Nothing, may I find my All!

The modern version of Mephistopheles' witchcraft, employed by science, consists of theory and experiment, experiment and theory.

The remarkable ideas that science has retained through the centuries are a sort of lines on the picture of the world, that aid in finding the path from the known to the unknown. Each line serves as an axis on which scientific facts and guesses, discoveries and theories seem to be strung or threaded and become arranged into more or less orderly systems. I have tried to make more explicit this role of the idea that became the chief character of this book. Since we have employed the word "axis", let it lead us to the following comparison. The earth's axis, about which our Mother Earth rotates, was not so simple, in its time, to determine. In return, however, it is certainly apparent today in a globe used in school. Well, a book on science for the layman pertains to science as a globe pertains to our planet.

TO THE READER

Mir Publishers would be grateful for your comments on the content, translation and design of this book. We would also be pleased to receive any other suggestions you may wish to make.

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