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Contents

The Queen of the World and Her Shadow

Energy reigns over everything that occurs in infinite space and in the course of transient time. Energy, like a queen or goddess, irradiates its light over everything from a blade of grass in the field to a man of genius, endowing here and bereaving there, while remaining constant in quantity. Yet, where there is light, there is shade. Entropy is the name of the queen's shadow. Face to face with this phenomenon, Man cannot help feeling some vague fear: Entropy, like an evil spirit, tries to diminish or annihilate the best creations of that gracious spirit, Energy. We all are under the protection of Energy and all the potential victims of the latent poison of Entropy.... The quantity of Energy is constant, whereas the quantity of Entropy increases, depreciating Energy qualitatively. The sun is shining, but the shadows grow longer. Degradation, equalization, devaluation take place all around....

This imposing and pessimistic description of energy and entropy belongs to a popular-science author of the early twentieth century. Yet the first attempts to define these phenomena scientifically were made slightly over 120 years ago. Human beings had been making use of what is now called energy for thousands of years before that, although they were unconcerned with the nature of the phenomenon and ignorant not only of the term but of the notion itself. As for entropy, the concept of it was completely beyond the limits of mental and empirical reasoning at the time.

Watching a stone fall, shooting an arrow, and later, warming up at a fire, ancient humans were unaware that such phenomena were due to the expenditure of different forms of a certain energy (today we call these gravitational, elastic, and chemical energy respectively)

Gradually humans learned to discover certain inherent causalities between simple empirical observations, and later they were able to arrange them into more comprehensive theories which demonstrated the real interdependence of phenomena in the environment and brought to nothing religious and mystical 'explanations'. This became possible because of the formulation of general abstract definition, i.e. notions such as 'water', 'earth', 'fire', 'force', 'heat', and so on, which became the fundamentals of science. These notions had been crystallizing in the human mind for thousands of years as the result of numerous observations, practical experience, and developments in technology and technological theory.

The formulation of notions such as 'energy' and 'entropy', as well as the related concepts of 'force', 'work of force', and 'momentum', is inseparable from the development of practical power engineering. This process can be divided into five periods. The first period began in the early ages of human history and ended between the fifth and the seventh century. Humans used their muscular force (provided by the chemical energy of fauna and flora contained in food), solar heat, and later, fire. During the second period, which lasted from the eighth to the eighteenth century, the invention of the waterwheel and the windmill shifted part of this work to moving water and wind. The third period started roughly in the eighteenth century and ended in 1943. The prime force during this stage was the 'motive power of fire', while the nonrenewable chemical energy of fossil fuels (coal, oil, natural gas, and so on) was the principal source of power. The fourth period, the modern, began in 1943. This era is characterized by the rapid development and extensive use of nuclear power, exhaustion of chemical energy resources, and pollution of the environment.

Should we fail to discover new sources of power, the human race may have to face a fifth period, when all nonrenewable chemical energy and nuclear power resources are exhausted and people have to live in a state of dynamic parity with only renewable resources at their disposal. These include solar radiation, flow of sea and river waters, wind power, geothermal power, and chemical energy of vegetation.

Muscular force was measured as a quantity of pressure or thrust. It was, thus, understood in its modern meaning as a measure of the interaction of bodies, for example, the interaction of horse and cart. We know now that the stronger the force and the longer the path of its application, the more the work done. Hence, mechanical work is the product of force and the path of its application point (this is true when the directions of force application and motion coincide; if they do not, it is necessary to multiply the product obtained by their multiplication by the cosine of the angle between them). Power is defined as the amount of work produced in a given unit of time.

New forms of interaction have since been discovered. These include four elementary forms: nuclear, electromagnetic, weak (neutrino), and ultra-weak (gravitational) interaction and their various derivatives. The forms mentioned have respective forces and specific expressions in terms of work.

For a long time work and power were not considered separate notions and were defined by the single term 'force'. Thus, a unit of power still exists called 'horsepower' (hp), equal to 75 kgf-m/s. These units of force were applied increasingly as our ancestors mastered new methods of labor such as housing and bridge construction, various crafts, agriculture, weeding, and so forth. The need to measure the intensity of the mechanical motion of an arrow or a thrown stone resulted in the development of another notion, 'momentum', currently defined as the product of a body mass and the velocity vector (dependent on direction) and expressed as $m\omega$. When steam engines were invented to convert the heat due to fuel combustion into mechanical work, the 'motive power of fire' found an even wider application, and the term 'force' acquired a third meaning: energy, i.e. a source of 'active power', a source of work production.

Later, the energy of a moving system (a falling stone or a gas, for example) was called 'kinetic energy'. The term 'potential energy' was used to describe the energy of a system brought to a state in which it is capable of motion, although the motion may not yet have occurred (e.g. a stone raised above the ground or a gas compressed in a cylinder). After the discovery and investigation of forms of motion other than mechanical (for example, electric, electromagnetic, chemical, and thermal motion), scientists viewed energy as the common scalar (i.e. independent of direction) measure of these forms of motion.

Once they had learned to distinguish between forms of matter and its motion, as well as forms of interaction, researchers and engineers began to use the terms 'mechanical energy', 'electric energy', 'chemical energy', and so forth, widely. Thus, one more notion, that of 'forms of energy', appeared spontaneously, although the definition of this concept still remains vague. At the same time it was discovered that regardless of what changes took place in the material world, they were always accompanied by energy transition or conversion of its forms.

With the discovery, between 1845 and 1847, of the principle of conservation of energy during its transformations, the importance of energy in human life and progress was fully recognized, and scientists gave energy the romantic name of the 'Queen of the World'. Having noticed that all forms of energy convert into heat which is shared with colder bodies and dissipates afterwards in the environment, where it then radiates into outer space, scholars discovered entropy, a measure of the degradation of energy, twenty years later. The more energy degrades, the higher the level of entropy.

Both energy and entropy are words of Greek origin. The prefix *en* means 'in' or 'content', *ergon* means 'work', and *trepein* means 'to turn, change'. Scientists selected these terms to reflect the nature of their respective notions. A change in energy $\Delta E = E_1 - E_2$ in an isolated system indicates the maximum amount of work A_{max} that the system can theoretically produce in transition from state *1* to state *2*. A change in entropy $\Delta S = S_2 - S_1$ represents the store of energy ΔE converted into heat and dissipating, i.e. $Q_0 = T_0 \Delta S$. Under real conditions of transition and at T_0 ambient temperature, this store diminishes the amount of the actual work A_a to $A_a = A_{max} - T_0 \Delta S$. Thus, we may say that the change in entropy characterizes the amount of energy degradation in the process of transformation.

Two forms of energy transition exist: work production and heat exchange. Energy transformation may occur in the first case only, while energy is transferred unchanged in the second case in the form of heat (provided a temperature difference exists, and the transfer is always to bodies with the lowest temperature in the system).

The change in energy in a system is conditioned merely by the difference of its values in the initial and final states of transition. If this were not true, the system would be a source of energy out of 'nothing', which contradicts the principle of conservation of energy. Entropy is similarly a function of the state of the system. Yet the amount of heat $Q = \int T\,dS$ that expresses the 'loss' of energy depends upon the process in progress, while both the amount of heat that dissipates as a result of direct heat exchange between the system and the environment and the amount of heat that is released and dissipates as a result of friction depend equally on that factor. Thus the actual value of work also depends on the process and is always less than the maximum value, i.e. the change in energy in the system. The difference between these two values equals the energy losses 'through heat' because of friction and heat exchange. But even the energy spent on work production then dissipates, by friction and heat exchange, into the environment, where entropy continues to increase. Thus all the energy of gasoline which is converted in an automobile engine, first into heat and thereafter into mechanical energy, finally dissipates into the atmosphere as a result of the friction of the body and wheels against the air and ground.

Since all real processes are accompanied by friction and heat exchange, entropy continuously increases (naturally, only in those isolated systems which receive no energy from outside). Some scientists therefore concluded that eventually, perhaps after a very long time, all the energy available on this planet and in other parts of the universe would convert to heat. According to this theory, the even distribution of heat between terrestrial and universal bodies would result in temperature equalization and the complete halt of all energy transformations, i.e. to a 'heat death of the universe'.

The theory did not take into consideration the infinity of the universe, however, where the processes of energy degradation and concentration alternate in time and space. The concept of infinity is necessary to account for stores of energy on the Earth and in the Solar system. In fact, a natural process of energy concentration and entropy decrease is currently occurring on the Earth. In this process of photosynthesis the dissipated energy of solar radiation is transformed into the concentrated chemical energy in green plants. A further decrease in entropy occurs in animal and human organisms, the most sophisticated systems on Earth, during food digestion and assimilation.

L. Boltzmann, an Austrian physicist, used molecular-kinetic theory to prove that the principle of entropy increase (energy degradation) is not applicable to the universe since it is valid for statistical systems only, i.e. systems composed of a large number of particles moving chaotically, which behave in conformity with the principles of probability theory. The increase in entropy in such systems indicates the most likely direction of the processes but does not preclude the possibility of low-probability events, i.e. fluctuations (when entropy decreases), and can account for such a possibility if necessary. Thus, as a physicist once said, in the gigantic factory of natural processes, the principle of entropy increase acts as factory manager, determining the type and kind of business transaction performed, while the principle of conservation of energy plays the role of accountant, settling balances of debit and credit.

As has been mentioned above, the formation and development of the notions of 'energy' and 'entropy' are essential to the practice and theory of power engineering, the latter being the cornerstone of scientific and technical progress closely related to political, economic, philosophical, religious, psychological, and other social phenomena. History demonstrates that these phenomena may both detain progress and accelerate it. The struggle of the new against the old, truth against lies, science against prejudice, and good against evil fills all of human history and continues to this day. Therefore, studies of scientific and technological developments of the past and present and, even more important, projections for the future, are incomplete if they fail to account for specifics of historical social development. The role of outstanding philosophers and researchers cannot be overlooked either. The Greek philosopher Democritus, for example, expressed scientists' tireless longing for verity when he said: "I would rather discover the real cause of at least one phenomenon than become the King of Persia." Lenin, who seconded the idea 2400 years later, wrote: "... there has never been, nor can there be, any human search for truth without human emotions."

Only from such a viewpoint can the development of Energy and Entropy on our planet be traced. That will be our further subject, and we shall proceed, bearing in mind, however, that the Queen of the World and her Shadow came out of darkness full of uncertainty into broad daylight only about the second half of the nineteenth century, after centuries of work by talented philosophers, researchers, and engineers. Before that, energy and entropy had ruled nature and human society invisibly and secretly, under various names such as forces of gods and souls, action, activity, momentum, impetus, work, quantity of motion, monads, live and dead forces of nature, and so forth, or had no names at all.

The works of K. Marx, F. Engels, and V. I. Lenin contributed fundamentally to the establishment and further development of these notions. Marxist-Leninist theory defines matter as an objective reality that exists independently of our consciousness while being reflected in it. This definition is clarified and supplemented by natural-science data about the structure and characteristics of matter. Cognition of these aspects means cognition of matter itself. Matter, which is inseparably linked with motion, space, and time, is capable of self-development and is quantitatively and qualitatively infinite.

Various sciences concern the motion of matter, which takes a number of forms. New features and peculiarities of matter are constantly being discovered. Thus, energy, as a common measure of the motion of matter, and entropy, as a common measure of energy degradation, are characteristics of matter and can be neither identified with nor separated from it. The theory of energy and entropy developed on this very basis is now successfully applied to problems arising in the process of the scientific and technical revolution.

Whatever an enemy could do to his enemy,
Or a hater to the hated,
A thought erroneously directed could do still worse.

Dhammapada, Chapter III on Thought
(4th century B.C.)

The Man of Reason Showed in the Mirror of the Universe

The Earth emerged out of chaos, a cosmic nebula formed by chance. It came out of a clot of unbalance, a fluctuation in the infinite ocean of cosmic matter. The age of the Earth is assessed at between 4.5 and 5 billion years. The Earth's crust was formed during the first 1.5 to 2 billion years. Algae, bacteria, and Protozoa were the first to appear 3 billion years ago. Corals, sponges, Brachiopoda, Bryozoa, and Echinodermata came into being 500 million years ago, ferns and fungi turned up 350 million years ago, insects came 300 million years ago, reptiles (dinosaurs and others) appeared 250 million years ago, flowering plants and birds presented themselves 150 million years ago, mammals came 100 million years ago ... and at last

...a raving vortex of events
Has rapidly transformed the continents.
The slopes and peaks of capes stood bold and fearless.
The monstrous beasts have gone for good, the ages passed,
The strikes and falls of ancient struggle weakened.
And after thousands of years full of bad and worse
The Man of reason showed in the mirror of the universe.

E. Wernharn

This happened about four million years ago, though not in one day. The process of anthropogenesis, i.e. birth and evolution of man, took hundreds of thousands of years. According to Marxist theory, the whole of human history is a continuous alteration of human nature. Humans had to fight for existence from their first steps on Earth. Hence, force became one of the first ideas and then notions to have entered their still awakening minds. The first ancestors of modern man fed themselves with whatever they could gather. They began, gradually, to walk upright, which gave them 'free hands'. With these hands, still absolutely 'bare', man made his first killing of a weaker and slower animal and became a hunter. He sharpened then a stone and fixed it on a stick to have invented, by doing so, an axe. Some time later, man made a spear a deadly weapon which served him for many thousand years thereafter.

The all devouring force of fire did not yield to man for a long time. Legends tell that fire was stolen from the gods and hidden in hollow pieces of wood and stone, that is why it can be extracted from these objects by friction. F. Engels said that the generation of fire by friction gave man control over one of the forces of nature for the first time, and thereby separated him from the animal kingdom. Since the task of making and keeping fire was a hard one for early humans, the first firekeepers appeared and were relieved of other tasks and duties. These officers tried continuously to elevate and strengthen their profitable position. For that purpose, they started to 'govern' other 'forces' and 'represent' on Earth not only the God of fire but also other gods. Thus priests came into being as the first clergymen and ideologists.

The primitive man knew very little of the surrounding reality. He substituted faith for ignorance which asked for no proof. All religions are based on such faith in a systematized form. The 'sources' of force, i.e. gods, invisible and omnipresent, were the principal object of fantastic reasoning. The gods were supposed then to be as real as the energy of gasoline or uranium is real today. The visible natural world seemed to humans a mere and insignificant part of a vast and invisible supernatural world the 'control' of which was exercised by means of sacrifices, ritual dances, etc.

F. Engels wrote in *Anti-Dühring* that all religion, however, is nothing but the fantastic reflection in men's minds of those external forces which control their daily life, a reflection in which the terrestrial forces assume the form of supernatural forces. In the beginning of history it was the forces of nature which were first so reflected, and which in the course of further evolution under-went the most manifold and varied personifications among the various peoples. This early process has been traced back by comparative mythology. But it is not long before, side by side with the forces of nature, social forces begin to be active, forces which confront man as equally alien and at first equally inexplicable, dominating him with the same apparent natural necessity as the forces of nature themselves. The fantastic figures, which at first only reflected the mysterious forces of nature, at this point acquire social attributes, become representatives of the forces of history.

The life of humans was drastically changed when they learned to use fire. They could bake bread then from cereal grains. A first mill was soon invented which consisted of two millstones, one of which was rotated manually. Humans observed the action of fire and discovered gradually that it was possible to turn ores into metals, and the Bronze Age succeeded the Stone Age to be followed by the Iron Age. Humans discovered glass after having learned to melt gold (glass being a by-product in the process of alloying gold-bearing sand with sodium carbonate). The art of glass processing reached a very high level in ancient China, Egypt, and later, in the Mediterranean.

New tools were gradually invented. At first tools to catch wild animals appeared, such as a harpoon, lasso, bolas (a weapon consisting of two or more balls or stones attached to the ends of a cord), a throw-over net, a loop thrown by hand, and others. The observations and experience of humans resulted in the invention of self-acting devices replacing man, i.e. machines. That allowed Benjamin Franklin to determine man as an animal making tools, and K. Marx specified: "...making instruments of production with the help of the instruments themselves."

As we know, any machine is a transformer of energy by nature. However, machines are classified into engines (energy-converting machinery) and machine tools. Julius Lipps (b. 1895, d. 1950), a German ethnographer, proved that the water mill should not be considered the first machine to have been invented, since, in fact, it was the self-acting trap. Traps may be classified by the mode of operation into four groups. The traps of the first group work under the pressure of the weight of animals (these are pits), the traps of the second group exploit the weight of objects killing animals (stones and trees), the traps of the third group engage the elastic force of a bent branch or tree (arc-like springs), and the traps of the fourth group operate by using the elastic force of a twisting mechanism. Spring devices were applied to make fire, to operate processing machines, and to execute slaves and prisoners of war. Machine-type traps appeared between ten and twenty thousand years ago. This means that humans had already been aware of the principles of the lever and could apply them at that time.

It was only in the 4th century that first waterwheels were made, and windmills appeared in the 10th century. These devices, together with muscular force, dominated power engineering up to the 18th century when the steam engine succeeded. Nevertheless, 46,000 waterwheels had been in operation in Russia by 1917 and constituted 40% of the country's total machine power (railway and water transport excluded since the steam engine and, later, the internal combustion engine had widely spread in both industries by that time).

Cultivation of cereals and domestication of animals started 10,000 years ago. It was then that the first real division of labor took place. The farmers had their own supernatural forces and gods, the cattle-breeders had their special ones.

Each man made his own tools for hunting, cattle-breeding, and farming for many thousands of years, but with time individuals appeared specifically skilled in making tools, and these craftsmen made tool production their sole occupation. Thus, the second important division of labor occurred at the highest stage of development of the primitive communal system, i.e. craft was separated from farming.

The more the power of man over nature spread, the more his potential power over his fellowmen grew. The exchange of goods, which had started by that time, resulted in the accumulation of wealth in the hands of the few and the impoverishment of the many. The minority of the population got control over the means of production and thus commanded the life and freedom of the majority. The classes of slave-owners and slaves were formed.

The slave-owners enjoyed free time which could be used for arts and science, although the latter was of no practical need as the labor of slaves cost nothing and required neither facilitation nor increase in productivity. Aristotle, one of the most prominent ancient Greek thinkers (b. 384, d. 322 B.C.), wrote: "It was then, when we had got almost all necessary things and things to make life easier and to pass the time, that rational thinking ... became the object of search.... But as we call a free man that one who exists for himself, so we turn to science since it is the only thing which is free ... it alone exists for itself."

Thus humans lived on Earth for hundreds of thousands of years hunting, farming, trading, warring, building houses, bridges, canals, temples, palaces, and tombs, and never touching the unrenewable sources of energy accumulated in the interiors of the planet. But this did not prevent them from creating unique edifices such as Egyptian pyramids (one of the 'seven miracles of the world') which were built 5000 years ago in the time span of a mere 20 years. The sole energy employed in construction was the chemical energy of food which transformed into mechanical muscular energy in the organisms of animals and slaves, and the only mechanisms were the inclined plane and lever. The greatest of pyramids, that of Cheops, is 230 m long and is as high as a modern 50-storey skyscraper. It was assembled of 2.3 million blocks, each weighing 1.5 tonnes on the average (which is the weight of 1.5 'Lada' cars), and the heaviest of blocks weighed 15 tonnes! The slits between blocks do not exceed 0.5 cm, and the length of the sides of the base differs by 2 cm only, which is a mere 0.0009 per cent! The faces of the pyramid are directed precisely at the four compass points.

The methods applied to erect these edifices, so perfect technically and aesthetically, are long forgotten. The only thing clear is that the construction of them required a great expenditure of energy. It is not by chance that some experts related, recently, many creations of ancient humans to the talent and force of certain 'visitors from space'.

From the Forces of Gods to the Forces of Souls in Every Object

It is said that the exposure of a lie is the first stage of wisdom and the cognition of truth is only the second stage. It is not surprising, therefore, that the history of science is the history of a most merciless struggle. The way to truth went against mystical beliefs spontaneously formed and religious dogmata officially proclaimed, against the ignorance of some and vicious vanity of others, against the psychological inertia and delusions of even great thinkers....

Humans thought, in the 'pre-science' period, that they 'knew everything', but science, even in its green years, deprived some of 'knowledge', others of social position, and still others of power. The accumulation of observations and tokens on the basis of which the first scientific ideas started to form began in prehistoric times. People of the Oriental slave-owning monarchies of Egypt, Babylonia, Assyria, as well as China and India, knew already several thousand years ago a lot of 'secrets of sages', which were passed from generation to generation, first orally and later (beginning with the 4th to 5th thousand years B.C.) in written form. These 'secrets' were closely interwoven with fantastic images. At that time five planets, their mode of motion, and a number of constellations had already been known. Sages could determine the periods of solar and lunar eclipses, solve simple, quadratic, and sometimes cubic equations, determine areas of figures. A calendar was compiled in which the year was divided into 12 months each having 30 days. Egyptian priests had a considerable practical knowledge of chemistry and medicine, they could also embalm dead bodies.

However, despite the abundance of accumulated facts, it was impossible at that time to move forward to the generalization of facts and to compose causally conditioned systems, i.e. to create the foundations of science, since the very probability of inherent regularities in nature was unthinkable. Everything in the world was controlled and moved by gods endowed with supernatural 'forces'.

The ancient Greeks made the first attempts to work out scientific views on the structure of the world, which was possible under the conditions of democracy and free-thinking that flourished in their slave-owning city-states between the 7th and 5th centuries B.C. (considering the electivity of administration, free discussion of any political issues, and a certain freedom of heathen religions).

F. Engels wrote that the manifold forms of Greek philosophy contain in embryo, in the nascent state, almost all later modes of outlook on the world. Theoretical natural science is therefore likewise forced to go back to the Greeks if it desires to trace the history of the origin and development of its modern fundamentals. Let us follow the same route.

The bloom of economic life in Greece began in the 6th century B.C. on the Mediterranean coast of Asia Minor in the cities of Miletus, Ephesus, Smyrna and on the islands of Chios and Samos which were populated by the Greeks of the Ionian tribe. Merchants and artisans composed the majority of residents of these cities situated near the Oriental centers of culture. It was in these cities, and later in other places, that the first philosophical schools began to form around great thinkers. The Greek sages doubted the existence of gods but felt yet no need for the practical application of their findings as they were still unable to arrange experiments correctly. Thus, they began to invent comprehensive theories of nature on the grounds of 'philosophical principles', these theories being known as 'natural-philosophical' systems of the world. The weakest point of these systems was the explanation of the origins and nature of the acting forces. Yet the Greeks tried, bravely and decisively, to separate nature from mysticism and to explain the former by 'real' spiritual or material elements which were often of a mechanistic or anthropomorphous character.

A democratic system was established in Athens at that time, and aristocrats dominated in Sparta. The Greek city-states won a war for independence against Persia in 449 B.C. and entered the period of their highest prosperity.

However, the Peloponnesian War broke out between

Athens and Sparta in 431 B.C. The war ended 25 years later with the victory of Sparta. Athens was also devastated by the Romans in 379 B.C.

Macedon rose from the ranks in the middle of the 4th century B.C. The king of Macedon, Alexander, conquered and established the empire which stretched from the Balkan peninsula to India. Before that he had ultimately defeated Persia. Yet, the empire broke into several Hellenistic monarchies after the death of Alexander in 323 B.C. The monarchies lasted up to the invasion by the Roman legions in 30 B.C. One of these monarchies, that of the Ptolemy kings in Egypt, included Alexandria (a city founded by Alexander the Great) which was a large economic and cultural center. In that city the development of ancient science focussed between the 3rd and 1st centuries B.C. This period was called the 'Hellenistic period' or the 'Alexandrian period'.

The most popular natural-philosophical schools of the time between the 7th and 6th centuries B.C. were the Ionian, Pythagorean, and Eleatic schools.

The Ionians were elemental materialists. Their idea of the world was that it was an integral whole in which all astronomical, physical, chemical, and biological phenomena stemmed from a common origin. Each of the systems which they developed was based on an 'elemental substance', i.e. earth, water, air, fire, or on a certain specific 'elemental matter' from which everything had developed under the 'impact' of heat, cold, dryness, and humidity. Should we investigate all possible combinations of these elements, we could derive, not by having to choke over dust in archives, all natural-philosophical systems of the time, and even some which had been missed.

Thales of Miletus (b. *c.* 640, d. *c.* 546 B.C.) considered water to be the 'source of all sources'. His successor, Anaximander (b. *c.* 610, d. *c.* 547 B.C.), believed in a certain 'elemental matter' called 'apeyron' (which means 'boundless'). Anaximenes (b. *c.* 588, d. *c.* 525 B.C.) treated air, the idea of Heraclitus of Ephesus (b. *c.* 540, d. *c.* 475 B.C.) was fire. All the theories were based on the idea of the development of the world which was expressed by Anaximander, for example, as follows: water was formed from a moist element, fish appeared in water, and when the water 'dried out', the world and other creatures were formed; man stemmed from fish and came out of water onto dry land. Heraclitus, the founder of dialectics, said: "The world, the only of its kind, was created not by the gods and not by man, but it was, is, and will be an ever-living fire which ignites regularly and dies down regularly." V. I. Lenin said that this approaches dialectical materialism almost completely.

There was another famous school, at approximately the same time, in the city of Crotona on the coast of the picturesque Gulf of Taranto. The school was headed by Pythagoras of Samos (b. *c.* 570, d. *c.* 500 B.C.), a former disciple of the Ionian school who had switched over to the positions of idealism. The Pythagoreans looked for the nature of surrounding objects and phenomena in numbers. Justice was a property of some numbers, soul was that of others, intelligence was a property of still others, and luck was symbolized by still others. Having started the investigation of numbers, the Pythagoreans noted the existence of quantitative dependencies in the world.

Later the idealistic approach was further extended and developed by Socrates (b. *c.* 470, d. 399 B.C.) and his disciple Plato (b. *c.* 427, d. *c.* 347 B.C.). Socrates held that the physical nature of things was incognizable. Hence his formula 'know thyself' and learn to live skilfully, which was the aim of one who had taken the trouble to be born. It should be noted, however, that he was unable to use this recommendation even for himself. Socrates was sentenced to death and died having drunk a cup of hemlock. The dialectics of Socrates was an art to reach verity by means of exposing controversies in the opponent's arguments, unlike the materialistic dialectics of Heraclitus. As to objective idealism, it was founded by Plato. He taught that the world of eternal unchangeable ideas formed the real being, and the world of changeable and transient things was a mere shadow of the world of ideas....

The third school was formed at the end of the 6th century B.C. in Elea, a Greek colony in southern Italy, and gained wide popularity. Xenophanes (b. *c.* 570, d. *c.* 478 B.C.) belonged to that school as did Parmenides

(b. *c.* 539, d. B.C.), Zeno (b. *c.* 495, d. *c.* 430 B.C.), and Melissus. They argued the Ionian theory of development and motion and pointed out the controversial character of motion, space, and time (especially Zeno did). They concluded therefrom that there was no motion and multiplicity of things, the being was uniform, continuous, motionless, and immutable.

The Eleatics influenced the so-called junior natural philosophers, the atomists. To these belonged Anaxagoras (b. *c.* 500, d. 428 B.C.), Empedocles (b. *c.* 490, d. 430 B.C.), Leucippus (b. *c.* 500, d. 440 B.C.), Democritus (b. *c.* 460, d. *c.* 370 B.C.), and Epicurus (b. 341, d. 270 B.C.). The above-mentioned philosophers acknowledged, in contrast to the Ionian school, the immutability of elementary substance, and, in contrast to the Eleatics, the multiplicity of things. Thus, Empedocles (as well as Aristotle did later) believed the basis of the world to be not one substance, but four substances simultaneously: earth, water, air, and fire, from different combinations of which everything was formed.

The atomistic theory was best developed in works by Democritus of Abdera and his teacher and friend, Leucippus. Democritus discarded the argument of Anaxagoras about the limitless fissionability of particles and declared that a nonfissionable particle, the atom (the Greek word is *atomos*), was the limit of fissionability. Elements differ by the type of atoms, i.e. by their form and weight. Each element is composed of atoms of one type, while compounds consist of compositions of atoms of the given elements (which is very close to the modern view). Everything in the surrounding world consists of empty space and a countless number of atoms. Out of that which does not exist, nothing would form, and that which exists cannot vanish without a trace. That is almost the modern definition of the principles of conservation of matter and energy! According to Democritus, all atoms move continuously while falling through the interminable space. As it happens, the larger atoms fall faster than the smaller atoms, collide with them, and produce lateral motion, or vortices, with the help of which atoms are composed into bodies. Vortices caused the formation of the universe.

Epicurus and ancient stoics such as Zeno of Citium, Chrysippus, and others extended the theory of Democritus and Leucippus. Epicurus denied the interference of gods in terrestrial affairs and believed that the aim of philosophy was the felicity of man, to reach which, he thought, the cognition of nature was necessary in order to relieve humans of the fear of gods and death.

Titus Lucretius Carus, a Roman philosopher and poet (b. *c.* 95, d. *c.* 55 B.C.), was an enthusiastic popularizer of the theory of ancient materialistic atomists, which he described in his poem *De rerum natura* ("On the Nature of Things").

These were the major principles of the ancient Greek theories of the composition of matter. It was much more complicated to explain the causes of the matter's motion and the natural origin of forces. There was still no hint of notions such as 'work', 'energy', and 'entropy' in those theories.

Despite the fact that the doctrines of the Ionian school deal with the idea of development, evolution, and motion of the world, they say nothing about the material origins of these processes, the sources of motion.

Thales believed the world to be full of gods and demons which control everything. He introduced, however, independent motive elements, 'souls'. His idea was that only 'animate objects' can generate motion. Hence, the magnet, the 'herculean stone', had a soul in which its power was concentrated.

Anaximander held that the cause of the formation and destruction of things was a conflict of opposites, which was ruled, as well as everything in the world, by a certain 'elemental matter' called 'apeyron'....

Heraclitus was the first to introduce fire as a material source of motion, i.e. thermal energy, or heat. He explained motion by the stages of the development of fire. "Everything is exchanged for fire and fire is exchanged for everything, as goods are exchanged for gold and gold is exchanged for goods...." It was Heraclitus, the founder of dialectics, who said: "Everything flows, everything changes" and "it is impossible to bathe twice in the same river."

Anaxagoras considered *nous* ('mind' or 'reason'), which itself was the smallest and cleanest of all things, to be the motive element. However, he assumed that internal forces of matter itself could produce primitive movements.

Empedocles divided the only all-motive power *nous* into two: the force of love (attraction), and the force of animosity (repulsion). This corresponded to the idea of love popular among the Greeks at that time. Personages of ancient Greek dramas by Aeschylus, Sophocles, Euripides, and others love passionately and hate fiercely one and the same person.

Democritus and Leucippus denied any forces acting outside atoms. Their doctrine proclaimed that atoms moved under the impact of their own 'forces' which seemed to have been the ancestors of the modern notion of energy.

Idealists believed that everything was moved by 'ideas' or a 'spirit', but even they came close to materialistic notions. Plato, for instance, tried to create his own, 'mathematical' system of life in contrast to the mechanistic system of life and being, which had been developed by Democritus and Leucippus. He defined the nature of all that existed as an ability to act. G. Leibniz would say 2100 years later: "Only that is real, which acts," and W. Ostwald would write more explicitly in 1895: "Our sensory organs react to the difference of energies between them and the environment."

Thus, the ancient thinkers came more or less close to the principles of conservation of matter and 'force' (energy). They introduced the idea of rigid causalities in nature and laid down the foundations of dialectics and the theory of cognition (movement from sensual perception to disclosure of causalities via thinking). The atomistic theory of the ancients contained fundamentals of the mechanistic world outlook formed between the 17th and 19th centuries.

Views on the structure of the universe, which no natural-philosophical system could do without, played an important role in the formulation of 'terrestrial' notions of 'energy' and 'entropy'. Plato even developed a doctrine of the 'parallelism' of all that occurs in space and on Earth. The doctrine stated that the position and motion of planets determined both the fates of individuals and all affairs on Earth. The flow of blood in the human organism, for instance, resembles the motion of heavenly bodies, as it is a circular process; metals have a certain relation to some planets, and so forth. According to Thales, the Earth floated in water like wood. Anaximander believed the form of the Earth to be that of a low cylinder and positioned the planet at the center of the universe where it was engirded by three fire rings: a solar ring, a lunar ring, and a ring of stars. The Pythagoreans, who considered the sphere to be the 'most perfect' geometrical figure, declared that the Earth was a sphere rotating around the Central Fire together with the Sun, the Moon, the Anti-Earth, and other planets. The Anti-Earth was invented because the number of world spheres, i.e. Mercury, Venus, Mars, Jupiter, Saturn, the Sun, the Moon, the stars, and the Earth, did not reach the 'holy number' of ten, and that made the explanation of eclipses more complicated.... Soon, however, a Greek natural philosopher, Heraclitus and an astronomer, Ecphantos (b. *c.* 350, d.), a Pythagorean, stated that the Earth was the center of the universe and explained the rotation of spheres by the rotation of the Earth around its axis. Anaxagoras took a step backwards. In his theory the Earth did not move but stayed at rest at the center of the universe. The Sun, planets, and stars were remote masses kept from falling only by the rotation of the firmament. Aristotle would later mix these theories adroitly and view the Earth, in the form of a sphere, at the center of the universe.

The first and the last, before Copernicus, heliocentric system of the world had already been designed at that time. The system placed the Sun at the center of the universe, and the planets and stars were placed around it. The Earth made one turn around the Sun in a year, and one turn around its axis every twenty-four hours. The system was developed by Aristarchus of Samos (b. *c.* 320, d. *c.* 250 B.C.), an astronomer who belonged to the Pythagorean school and was a resident of Alexandria for some time. It should be noted that he devised his system not speculatively, but on the ground of calculations of the distances between the Earth and the Sun and between the Earth and the Moon, as well as on the basis of calculations of the sizes of these bodies (in which the influence of the Pythagorean school is evident). Nobody, however, recognized the system, and N. Copernicus had to discover it anew 1800 years later, and G. Bruno and G. Galileo had to fight fiercely to prove the verity of it during the hard times of the Inquisition and Scholasticism.

We may also conclude that the 'free' heathen religion and democracy of the slave-owning system did not forgive persistence in defending scientific views and labelled them with this or that political meaning. Thus, Anaxagoras was sentenced to death for 'impiety' and it took the great efforts of Pericles, the archistrategist, i.e. the governor of Athens, who was a disciple of Anaxagoras, to change his teacher's death verdict to exile. Pythagoras was killed in a political conflict, as some legends tell, or fled to Metapontum and starved himself to death in the Temple to the Muses, according to others. Socrates was executed because his theory was thought dangerous for the democracy of Athens. When the aristocracy came to power in Athens and gods were again declared the makers of the existing order, the doctrines of Heraclitus, Democritus, and other materialists were labelled false, ridiculous, and heretic. Many philosophers were tried and sentenced, but Democritus, Aristarchus of Samos (later), and some others escaped the common lot by having left their native country. Empedocles, as Horace wrote, stepped into the fire-breething crater of the Etna volcano to gain sainthood. Even the great Aristotle, the teacher of Alexander the Great, was accused, in the traditional manner, of 'insulting the gods' and had to flee for his life from Athens to spend the rest of his life in exile, abandoned and forgotten by everybody.

Energy and 2000 Years of Walking About

The word 'energy' seems to appear for the first time in the works by Aristotle. However, his books were so frequently rewritten, translated, recited, and commented upon that we cannot feel confident about his authorship of the term. Furthermore, there was neither a clear definition nor a mathematical formulation and considerable application of this notion in his doctrines where it was but an 'active', or 'operative', element.

At that time, when machines were scarce, humans had to deal most frequently with gravity and friction dependent on the weight of bodies. Lifting mechanisms employed in theaters to deliver gods on the stage were one of the peculiar types of machines of the time (hence the expression 'a god out of a machine', i.e. an aritificial god). Gods appeared at the end of performances, staged by men or mannequins, and settled conflicts.

Time and speed, consequently, were important factors of lifting and lowering weights. Hence, Aristotle stated that the value of 'action', or 'active force' (F) is proportional to the weight of the moving body (P), the path of the body's motion (l), and is inversely proportional to the time of this motion (τ), that is $F = f\,(Pl/\tau) = f\,(P\omega)$, where $\omega = l/\tau$ is velocity.

This value is presently called 'power', but at that time the word 'force' (*dynamis* in Greek) had already been translated into Latin as *potentia*, then from Latin into French as *puissance* and into English as *power*. Hence the 'horse power', a unit of power.

The diversity of terms is not, however, a principal matter. This value could have been termed force as well as power, the name can be changed easily. The matter is that the definition of 'force' introduced by Aristotle brought about a lot of erroneous conclusions. Thus, for example, the velocity is zero when the force is equal to zero. This, however, contradicts the evident fact: an arrow shot from a bow continues its flight although the force of the bow-string does not act on it any longer. The same can be said about a stone launched from a catapult.

Aristotle settled this evident discrepancy as follows: the arrow is carried by the air which is set in motion by the released bow-string, and the stone is pushed by the air which fills the vacuum formed behind the stone. To support this argument, he adduced a thesis that "nature abhors a vacuum".

The above-mentioned definition of 'force' means that a heavier object would fall to the ground faster than a lighter object. It was only Galileo who managed to prove convincingly the erroneousness of this conclusion 2000 years later.

However, the erroneousness of Aristotle's definition of 'force' was understood by many even in his life time. During the Hellenistic period it was substituted by another, which was close to the notion of 'work' (or a later notion of 'vital force' which will be dealt with below). From Aristotle's formula the new definition may be obtained if we cross out time in the denominator. The formula would then read as follows: $F = f\ (Pl)$. The motion of a body was typically explained by applying a 'motive force' to the body at the moment of its start; when the 'force' was exhausted, the motion would stop.

Despite this and many other erroneous, and sometimes even absurd, ideas, the Aristotelian doctrine survived the periods of oblivion and the periods of almost global expansion and dominated human minds for 2000 years! This striking phenomenon calls for a closer acquaintance with the author himself, the son of his epoch and a prominent historical personality, as well as the fundamentals of his teachings.

The contemporaries and biographers of Aristotle described him as having thin legs and small eyes. He lisped and had a habit of wearing bright clothes and rings and had his hair cut in a most unusual way. His speech was full of sarcasm, and, as Francis Bacon said, "He strangled his opponents in the manner of Oriental despots." Aristotle was born in the city of Stagira (hence his nickname 'the Stagirite') located in northern Greece. His father was a doctor and was appointed the physician to the court of Amyntas II, the king of Macedon. Aristotle inherited considerable wealth from his father and moved to Athens to enter the school of Plato at the age of seventeen. He spent twenty years there, up to the death of his teacher. This, however, did not prevent him from saying later: "Plato is dear to me, but truth is dearer still!"

The Macedonian king Philip II entrusted Aristotle with the education of his son Alexander who said later: "I honor Aristotle as high as my father in the sense that I owe my life to my father and I owe Aristotle everything which gives value to life." However, Alexander cared little for Aristotle after he came to the throne in 336 B.C.

Three years later he commanded his armies to launch the first campaign against Persia, and Aristotle returned to Athens. He founded there a school of his own, the Lyceum, so called because Aristotle lectured in a hall near the Temple to Apollo Lyceius (Apollo the Wolf-God). (Hence the word 'lyceum' for schools in prerevolutionary Russia and other countries. The French word 'lycée' stems from the same origin.) The school of Aristotle became one of the most prominent centers of enlightenment which existed for about 800 years! The students and followers of the school were called 'Peripatetics', which means 'walking about' in Greek, because Aristotle liked to lecture to his students and argue while walking in the school's garden.

Aristotle wrote 28 books such as *Physics* (8 books), *Metaphysics*, *Categories*, *Nicomachean Ethics*, *On the Soul*, *Politics*, *Prior* and *Posterior Analytics*, *Poetics*, *On the Generation of Animals*, *Organon* (on logic), *The Problems of Mechanics* (the latter was written, according to the recent evidence, in the 3rd century B.C. by one of his students), and others. Thus Aristotle initiated the division of sciences and left not a single issue in any field without an explanation.

He instructed his son to keep to the golden mean, he instructed poets not to copy life but 'organize' it, he taught thinkers the system of logic, he lectured scientists on the methods of science (each science has its own postulates, axioms, and so forth). Provided one possessed all the 28 books by Aristotle, he was relieved of the necessity to think independently and needed but time to learn the books by heart. It would take, however, more than one life to do so because of the volume of Aristotle's works, their perplexity and erroneousness of many arguments. That is why there were so many expositions and commentaries on the theory of Aristotle....

Although Stagirite's compositions combine the doctrines of many natural philosophers, there are no 'kernels' therein equal in scale to the dialectics of Heraclitus, the atomic theory of Democritus, the heliocentric system of Aristarchus of Samos, and so on. Furthermore, he extinguished these kernels completely. Thus, the so prolonged popularity of the Aristotelian doctrine can be accounted for only by unique historical conditions of the time when human life was full of religious and political passions and struggle for existence or enrichment. Moreover, the abundance of natural phenomena, the seeming logical exposition of facts, the comprehensiveness of arguments in which idealism was mixed with materialism excited the inert majority of dogmatic scientists and they defended Aristotle violently against attacks by thinking individuals, especially after the canonization of his theory in the 13th century.

Aristotle believed that only experience and observation provided material to deduce general principles, and logic was but an instrument which gave form to science. The objective of natural science is the explanation of what is rightly observed by our sensory organs. The experiment, however, was limited by primitive everyday experience, observation was the mere result of direct sensation, and explanation was nothing but 'rational' or theological reasoning. All this was due to the low level of science and technology of the time. Quantitative arguments were practically not applied, the technology of measurement was rudimentary.

Thus, the great principles turned into a groundless declaration to have drowned in the floods of speculative verbiage. W. Gilbert, G. Galileo, F. Bacon, and others had to discover and defend these principles anew in the 17th century.

Aristotle attacked the idealism of Plato, his teacher, but he himself stayed on idealistic and mystical positions, as we shall see below, when explaining the nature of forces and motion.

He believed, like Empedocles, that earth, water, air, and fire were the elements of all that existed. However, these elements themselves were formed from one principal substance, the elemental matter, under the impact of dryness or humidity, heat or cold. Thus, air is formed from water under the impact of heat, the cooling of air produces fog, the earth and stones are formed as a result of water drying out.

The elemental matter is passive and has to be combined with the active element, a form which turns probability into reality, to produce a certain thing. This process is also motion. The elements tend to return to 'their places'. Hence, the heaviest element, the earth, is situated at the center of the universe; water lies above earth, air lies above water, and the last layer is the lightest one, i.e. fire. This 'theory' led the mechanics of fluids to a deadlock, as it meant that water could not produce pressure on earth, and air could not produce pressure on water and earth.

Aristotle interpreted motion loosely and distinguished therein five elements: the motive element, the moved element, the direction, the starting point, and the objective. The objective determines the type of motion, i.e. the appearance, destruction, growth, decrease, qualitative change, and travel. The latter is divided into thrust, push, rotation, and displacement.

Like his predecessors, Aristotle considered the existing 'elemental matter' to be incapable of increasing or decreasing, it neither appears nor disappears, and is capable only of alteration. Hence, no type of motion can produce matter, inasmuch as motion which exists in nature can neither originate nor vanish because it is eternal. Thus, Aristotle, though speculatively and *a priori*, had introduced the principle of perpetuity of matter and motion (energy) long before Descartes (1620), Lomonosov (1750), Lavoisier (1770), and Mayer (1842).

'Natural' motion occurs by itself when objects strive to achieve their 'proper places'. Such motion on Earth includes only the motion of heavy objects downwards and the motion of light objects upwards. The circular motion of heavenly bodies is also natural, it is perfect and eternal. To substantiate the latter thesis, Aristotle invented the fifth element, 'ether', of which the heavens consist and for which circular motion is as natural as rectilinear motion is natural for terrestrial objects. All other motion is 'forced', produced by a push or pressure, and stops when the cause of it, i.e. force, is exhausted.

The motion of heavenly bodies is induced by a certain Elemental Force, or the Soul of the Universe (which was later succeeded by the Christian Lord). Everything in the heavens is permanent and perfect, in contrast to the Earth where everything changes. As the Earth is composed of the heaviest element, it cannot move and stays at the center of the universe. The spheric form of it is natural as all bodies tend to reach its center which is the focus of the universe. The spheres of heavenly bodies are positioned around the Earth. The nearest sphere is that of the Moon and the farthest sphere is that of motionless stars. The spheres rotate around the Earth with heavenly bodies fixed on them. The heavens and the sphere of motionless stars, which moves evenly and permanently in accordance with its nature, are composed of pure ether. The motion of planets, however, lacks the strict regularity because the substance of which they are composed is mixed with terrestrial elements. The heat and light emitted by the heavenly bodies are produced by friction against air, but since the bodies rotate together with the spheres, it is the air which glows, and the glow is the highest where the Sun is positioned.... This 'cosmogonic' system was, despite the seeming logic of it, one of the most backward even for the epoch of Aristotle.

Thus, a body capable of only forced motion remains at rest when force is not applied. It is, in fact, the first half of the principle of inertia. The second half: "or tends to persist in a state of uniform motion in a straight line" was finally determined only by Newton assisted by the preceding works of great thinkers such as Leonardo da Vinci, Galileo, Descartes, Huygens.

Force, according to Aristotle, is required not only to initiate and continue the motion of a body but also to alter the velocity of it. However, the value of force is proportional not to the rate of velocity alteration, i.e. acceleration (as Newton would prove it later), but to the value of velocity.... In his treatise *On the Heavens* Aristotle introduced the product of 'heaviness by velocity' as a measure of 'force'. He noted that the bodies, the values of the mentioned product of which are equal, produce equal action. Thus, already Aristotle hinted at the second (besides energy) measure of motion: momentum, although he believed it to be a 'measure of force'.

Aristotle (or some of his disciples to whom the authorship of the treatise *The Problems of Mechanics* is ascribed) did not overlook the problem of the difference in action of pressure and impact, which was a point of argument between the 17th and 18th centuries. He, however, was unable to answer the question more or less satisfactorily. The above-mentioned treatise introduced, perhaps for the first time, the term 'mechanics' which meant literally 'cleverness' in Greek. The figurative meaning of the word was a number of techniques, a skill which helped to turn the natural progress of things to the benefit of humans.

On that ground the lever was recognized as the principal element of mechanical devices such as scales, oars, rudders, sail-carrying masts, wedges, slings, dentist forceps, nutcrackers, and so forth. Thus static problems seem to have been considered from the positions of dynamics. In this manner, the motion of an equal-arm lever around the fulcrum was compared to that of an unequal-arm lever. In this case it was noted that the longer arm of the latter travels along the arc of a larger circle than that of the shorter arm's travel. It was hence concluded that the longer arm can lift a heavier weight as it travels a longer way.

Such was the idea of Aristotelian mechanics and that of his disciples. Thus we can see, despite the erroneousness of many of their views, how fundamental notions, ideas, questions, and problems were formed (although in embryo) already at that distant time. These notions required much work 2000 years thereafter to bring mechanics to its modern state. They include the notions of velocity, force, work, two measures of motion (momentum and energy), the principle of inertia (rest), and the principle of conservation of 'forces'.

Aristotle's definition of heat is also of interest for the subject of our discussion. Ancient atomists considered heat to be a substance (as well as sound, magnetism, and color), but Aristotle believed it to be the motion of particles. On the other hand, heat is a property of all bodies because it is the principal property of fire. That is why Aristotle distinguished two types of heat: the intrinsic and extrinsic heat.

As has been mentioned above, Aristotle's life ended tragically. He fled from Athens to escape the death sentence of the anti-Macedon party for "insult to gods" and to "save the fellow-citizens from the second (after the execution of Socrates—*G.A.*) offence of philosophy". The self-exile settled in Chalcis on the island of Euboea where he died soon at 63 years of age. His works were stored for some time in a cave near his house, but were moved later to the Alexandrian Museum. However, the original manuscripts did not get to the Museum. Sulla brought them later to Rome and had them rewritten in numerous copies in 70 B.C.

How would science have developed over the next 2000 years if the works of Aristotle had been destroyed? V. I. Lenin wrote that clericalism killed what was living in Aristotle and perpetuated what was dead. Thus people had to bear for many centuries this moral yoke forced by the Church on the whole Christian world, and sensible thinkers had to fight it fiercely, wasting their forces without success. On the other hand, the major external motive power of science, i.e. industry, made no headway, being satisfied with the sources of energy and other productive forces practically unchanged for thousands of years. Thus, science had no stimuli for development under the formed historical conditions, and could hardly have made any noticeable progress even if it had not been impeded by Aristotle.

"Give Me a Place to Stand and I Will Move the World!"

After the disintegration of the Greek Empire of Alexander the Great, Rome entered the historical arena. The Roman Empire was formed as a result of three Punic wars (264 to 146 B.C. with intervals) against the commercial-industrial city of Carthage, the army of which was composed of mercenaries. The agricultural Rome had a well-organized army and conquered almost all Mediterranean countries.

The economic and political life became more complicated. The long-accumulated discontent of slaves developed into a formidable riot headed by Spartacus in 73 to 71 B.C. The warfare technology was improved owing to the introduction of battering machines, catapults, ballistas, arrow launchers, and so forth. A Spartan general called them a "grave of the soldier's valor". The corps of engineers was formed in the army, and technical literature appeared.

These conditions, naturally, promoted a further accumulation of knowledge, and certain attempts were made to systematize it, though already not in the form of comprehensive natural-philosophical systems but in the form of specific sciences. Natural sciences separated from philosophy which had fallen into decay by that time, with the exclusion of the atheistic philosophy of Epicurus and Lucretius.

It should be noted that Epicurus, who lived about the same time as Aristotle, denied the latter's principle that "nature abhors a vacuum". Lucretius recited the words of Epicurus as follows: "Nature is composed of two things. These are firstly bodies and secondly empty space. A body can act, or action can be applied to a body, but bodies can be housed only by empty space." Hence Epicurus came to the most important anti-Aristotelian conclusion that all bodies would move at the same speed in a vacuum, because "they collide with nothing".

At that time formalism and logical mathematical constructions were becoming more and more fashionable, and activity connected with practical tasks was despised. So, the eyes of thinkers turned to the heavens where everything was a mystery easily accessible to mathematical processing not based on physical knowledge, because their day to day experience and low level of technology did not suggest any scientific problems, and possibilities of the speculative construction of systems of the world were exhausted. Thus, the terrestrial physics and mechanics were applied to the heavens even more widely than they had been by the ancient Greeks. Aristarchus of Samos, the above-mentioned author of the first heliocentric system, was a resident of Alexandria. Eratosthenes, the master of the Museum*, made a lot of important astronomical observations (there is a legend that he starved himself to death because of sudden blindness which he could not endure). Hipparchus contributed even more by having compiled a catalogue of 1022 stars which re-

* The Temple to the Muses, a great scientific center of Hellenism.

mained unimproved up to Tycho Brahe (the 16th century). The works of a Greek astronomer and mathematician, Hipparchus (b. *c.* 190, d. 125 B.C.), who applied the mechanical knowledge of the time to his astronomical research, indicated that many thinkers did not recognize Aristotle's explanation of the motion of objects. They considered that it was not air that imparted 'force' to the launched stone, thus inducing motion till the force was exhausted, but an active element, a 'motive power'.

Having discovered a lot of discrepancies in the Aristotelian system of the world, Alexandrian astronomers did not reject it but tried to amend and modify the system. In that matter an Alexandrian astronomer, mathematician, and geographer, Claudius Ptolemy, was most successful (the 2nd century). He suggested a geocentric system of the world laid down in 13 volumes of *The Mathematical Collection* which the Arabs later differentially called *Almagest* which means "The Great Astronomer". It took more than 1400 years to discredit this 'astronomer' and bring theory into accord with reality. Surprisingly, Ptolemy himself indicated more than once the probability of the Earth's motion and explained its motionlessness in his system by his desire to describe the heavens as seen from the Earth. This slip of the tongue could have cost him his life if made in the Middle Ages.

Euclid, a resident of Alexandria and a prominent ancient mathematician (the 4th to 3rd centuries B.C.), should also be mentioned here. His works contributed much to the development of the methods of science and, consequently, to the formation of the fundamentals of it, notions such as force, work, energy, momentum, and so on. The *Elements* by Euclid summed up everything done in mathematics before him. In that work Euclid developed a system of elementary geometry which is currently still valid and a system of deductive reasoning from the general to the particular, which was later accepted by the most prominent mathematicians, mechanics, physicists, and even philosophers. The deductive structure is still considered the best one for sciences as it makes the logic, contents, and potential capabilities of each science most comprehensive and explicit.

The *Elements* by Euclid influenced the great Archimedes significantly, i.e. the Archimedes of Syracuse (b. *c*. 287, d. 212 B.C.). Cicero, one of the Roman consuls and a prominent public speaker, lawyer, writer, and teacher of Julius Caesar, said about Euclid that his genius is incompatible with human nature. Archimedes got a schooling at home, in the house of his father who was an astronomer and a relative of Hiero II (the Syracusan king who reigned from 270 to 216 B.C.). Archimedes travelled to Alexandria to study. He gained such popularity there that he was called 'alpha', i.e. 'the first', while Eratosthenes, the master of the Museum, was honored with a mere 'beta' title, i.e. 'the second'.

In contrast to many scientists of that time, Archimedes made his studies on the basis of the combination of experience, observation, deductive logic, and Euclidean mathematics. On that ground he developed scientific theories of the equilibria of the lever and hard bodies in general, of floating bodies, etc., which he formulated in his works *On Plane Equilibria or Centers of Gravity of Planes* and *On Floating Bodies*. Archimedes introduced the notion of the 'center of gravity' and developed a technique to determine the centers of gravity of planes. The reasoning of Archimedes is as strict and logical as that of Euclid. He formulates first a number of postulates and axioms and then proves theorems, often employing the methods of geometry. Thus, he based the theory of equilibria on seven postulates, some of which he used to develop the principle of the lever. Having proved several auxiliary theorems, Archimedes proved the principal one, i.e. the principle of the lever for commensurable weights, which reads: the commensurable weights are balanced on lengths which are inversely proportional to the weights.

The Archimedes' outcry "Eureka!" (I've found it!) became a catchword. Archimedes was taking a bath when he came to the idea how to determine whether the king's crown just received from the goldsmith was really all gold or contained a grafting admixture of silver. The idea, however, became the basis of deductive reasoning which led him to the discovery of the famous principle of hydrostatics: A body lighter than fluid is buoyed up with a force which is equal to the excess of the weight of the fluid taken in the volume of the body over the weight of the body itself; a body heavier than fluid sinks to the bottom of the vessel and loses as much weight as that of the fluid taken in the volume of the body.

As we know, Aristotle expressed 'force' as the product of the body's weight by the velocity of its motion, the so-called 'dynamic' expression. Archimedes used the principle of the lever, which he developed theoretically, on the basis of the theory of equilibrium, i.e. statics. Hence the force in his formula is equal to the product of the body's weight by the path of its travel, which presently means work. Thus, Aristotle's idea of 'force' (or power) is closer to the notion of 'energy', while Archimedes' idea of 'force' is closer to the modern notion of force.

Archimedes brilliantly developed the theory of the multiplication of forces on the basis of the principle of the lever, which was one of the most important problems of that time. He realized the idea in almost 40 inventions such as the pulley block, water-lifting screw, military machines, etc.

He said the phrase which made the title of this section after having managed to launch a ship with the help of a complex system of primitive mechanisms, which 300 men could not do with their muscular force.

Moreover, he invented and constructed the famous 'Sphere', a mechanical planetarium imitating the motion of heavenly bodies and even solar and lunar eclipses. Cicero, who saw the Sphere 150 years later, was so impressed that he described it in his political-philosophical treatise *On the State*. The Sphere is supposed to have been activated by a pneumatic or steam engine.

Devices and machines constructed by Archimedes were always a sensation. They were also employed during the siege of Syracuse by the Romans in 215 B.C. The defenders of the city used them to shower the enemy with stones and arrows launched from the walls, to impede the battering machines coming near the walls, and to capsize sailboats and galleys. Roman soldiers immediately retreated when they saw a log or a rope on the wall. As a result, the siege lasted eight months. Polybius, an ancient historian, wrote: "...so great the power of one man was, so great the impact of his genius was! If it were not for Archimedes, just an old man, Syracuse would have surrendered to the Romans attacking the city from sea and dry land after the first attack." Although the legend that Archimedes burned down the Roman fleet by reflectors seems dubious, experiments carried out in 1973 demonstrated the probability of such a trick.

Archimedes died as he lived. Being deeply absorbed in the solution of one more task, he refused to follow a Roman soldier to the general Mercellus and the soldier thrust a sword in his back. The Sphere and other machines were taken to the Temple to the Valor in Rome as trophies of war and were stored there, surprising later generations for 500 years....

The Birth of the 'Motive Power of Fire'

The Roman Empire dominated the world of that time, but Rome itself was shaken by political, military, and religious conflicts. Rome was satisfied with productive forces practically unchanged after many ages of slave labor. The precedent of Archimedes, who had demonstrated the great potential of the mathematization of science and its connection with practice, was not understood as it should have been, because the society was not ready yet to accept it. Creative work and thinking fell into decay as few were interested in the study of 'dead' nature when life was so turbulent and full of passions. However, charlatan sciences such as astrology and magic prospered and expanded.

The second period of scientific and cultural bloom, known as the Alexandrian, or Hellenistic, period, followed the ancient Greek period and ended in 30 B.C. after the conquest of Egypt by the Romans.

The emperor Augustus (b. 63 B.C., d. 14 A.D.) established a military dictatorship and enjoyed power similar to that of a monarch, although he preserved nominally republican institutions. Augustus was not in the least inclined to tolerate the freethinking of Alexandrian scientists and turned to ancient Greek philosophy for the ideological background of his regime, inasmuch as Andronicus of Rhodes, the eleventh successor to Aristotle at the Lyceum, had published shortly before that the works of his teacher, brought by Sulla to Rome as a trophy of war. Thus, a new wave of interest in Aristotelian natural philosophy was stirred up after 200 years of oblivion, and achievements of the Alexandrian period were considered nearly seditious....

Before that, however, two Alexandrian mechanics, Ctesibius (a former barber) and Hero (a mathematician), had managed to discover a completely new branch of science, pneumatic- and heat-and-power engineering, and to further develop hydromechanics, which placed them 1800 years ahead of their time. It should be noted that their works consisted not of speculative reasoning but exclusively of experiments which were well based theoretically and lacked only measurements and quantitative relationships.

Ctesibius invented and constructed a prototype of a pneumatic gun, a force pump, a water clock, and even a water organ. Hero designed and made the first heat engine, a prototype of the steam reaction turbine, which he called 'eolopyles' (Eol was the god of the winds and 'pyles' means 'ball' or 'sphere'. It was believed at that time that heating of water generated not steam but air). That achievement was the most prominent one among numerous pneumatic and steam devices constructed by Hero. The device was made in the form of a metallic sphere with open-ended pipes soldered in opposite hemispheres. The ends of the pipes were turned to opposite sides. The sphere was filled with water and the water was boiled. Steam thrust from the pipes generated reaction propulsion, and the sphere rotated on pipe-like supports.

Hero is supposed to have been a disciple of Ctesibius, but the teacher remained a practical worker, while the student turned to theory. Hero described the devices known before him and those invented by Ctesibius and himself in a treatise entitled *Pneumatica*. He also explained theoretical principles of the operation of the devices described. Surprisingly, P. Musschenbroek, a prominent physicist, declared in 1751 that pneumatics was a part of philosophy concerning the Lord, spirits, angels, and the souls of humans and animals. What a regress of science after 1900 years!

Hero wrote in his treatise: "I thought it necessary to convey all information available on this subject (on air—

G.A.) and add to it our own findings. This will be a good service to those who would wish to study mathematics, and moreover, ... this will be a great help in practice and cause great surprise of the public."

Hero based his theoretical conclusions on the ideas of atomists about the existence of a vacuum between particles. He wrote: "Some individuals hold that a vacuum does not exist at all, others believe that a vacuum cannot occupy the whole space but may concentrate in the intervals between the particles of air, water, fire, and other bodies. We favor the latter idea...." and "If it were not true, how could light, heat or other material forces penetrate water, air, and other bodies?" That is why the "mixture of water and wine is a result of the penetration of one liquid's particles into the pores of the other" and "compression and expansion are the processes of narrowing and widening of pores while the size of the particles of the body remains constant". A body occupies its natural volume in the absence of any external force and "when we fill an empty vessel with water, we drive as much air out of it as there is water poured into it", and so forth. The heating of bodies is, according to Hero, filling their pores with a 'fire body'.

In 76 sections of his book Hero described a multitude of pneumatic, thermal, and hydraulic devices and toys such as pumps, siphons, automatically opening doors, singing birds, fountains, steam tops, eolopyles, and so forth.

We see here a unique phenomenon in the evolution of science and power engineering. In the first place, it was an unprecedented application of the *experimental* approach to research work on so large a scale, in contrast to the ancient Greek speculative natural philosophy. Moreover, it was the first deliberate and active attempt to generate *artificial forces* (nowadays we would call them 'types of energy') of compressed air and steam, nonexistent in nature, and use them practically in real devices. It was also an example, experimentally proved, of the wide possibilities of the *practical* application of these forces.

Thus, we may say that a *quiet, almost unnoticed* revolution took place in the principles of the generation of the 'motive power' as early as between the 2nd and 1st centuries B.C. A method to transform heat generated by the combustion of an organic fuel into mechanical work was discovered and tested experimentally; moreover, a working model of a practically universal heat engine was constructed (eolopyles). It would have been possible, thus, for the industrial revolution of the 17th and 18th centuries to have occurred several ages earlier if progress depended only upon scientific and technical discoveries....

In the Gloom of Religious and Political Cataclysms

The burden of human passions, however, proved stronger than reason. Christianity, a newly born religious doctrine, which introduced monotheism instead of multitheism, launched a campaign against the dying heathenism and concentrated all energy of people on that struggle. The very thinking about material things of nature became criminal since the spiritual life of men should be filled with faith. Eusebius of Caesares, one of the paters of the holy Church, wrote about the scientific works of ancient Greeks: "We value these things so low not because we are ignorant of them, but because we despise these useless works of the ancients." Another one, Augustine, said: "It would have been better if I'd never heard the name of that Democritus!" One more theologian, F. Lactantius, wrote: "How could people be so irrational to believe that on the opposite side of the Earth, grains and trees grow with their tops down and people walk with their feet above their head? The Holy Writ does not mention such creatures among the descendants of Adam" (from the treatise *De ira Dei*, i.e. "On False Wisdom", 340 A.D.).

As a result, the service to Rome, a pillar of power, and then to Christianity, a pillar of faith, delayed the development of science and technology for hundreds of years.... Tyrants succeeded tyrants, one religion, or a variant of it, with the help of which tyrants came to power, was defeated by another. Being overwhelmed with lust for power and glory, with fanatical faith and persecution of dissidents, struggle for enrichment and self-preservation, cold and hot wars, conspiracies and intrigues, mankind got along very well without steam and internal combustion engines, TV sets, cars and aircraft, not to mention atomic energy.

A powerful stream of Germanic, Sarmatian, Slavic, and other tribes' migration to the West (between the 4th and 7th centuries) extinguished the last remnants of the slave-owning Roman Empire. The Empire disintegrated into the West Roman Empire and the East Roman Empire (the Byzantine Empire) in 395. Soon, however, the Western Goths devastated Rome, and in 476 Odoacer, chief of the Scythians, dethroned the last emperor of the West Roman Empire, Romulus Augustulus. The Byzantine Empire was conquered by the Turks only in 1453.

Between the 4th and 7th centuries, Byzantium was a decaying slave-owning state and then a feudal empire occupying a vast territory and populated by many peoples. The emperor enjoyed unlimited power supported by the spiritual authority of the Church. A part of Byzantium, including Constantinople, was conquered by European feudals, participants of the 4th Crusade, in 1204, and the Latin Empire was established. However, the Byzantine Empire was restored 21 years later.

Byzantium maintained the heritage of the ancient world better than other countries did, and became an important cultural center of the Middle Ages. Nevertheless, the emperor Justinian I prohibited the Athenian philosophical schools in 529, and the activities of Aristotle's Lyceum were terminated. Alexandria, a center of science and culture, completely collapsed. Its library, the greatest one in the world at that time, was partly burned by Julius Caesar in 47 B.C., was further destroyed by fanatical Christians in 390, and finally demolished by fanatical Moslems in 640. Mohammed said: "If sciences teach what is said in the Koran, they are superfluous, if they teach otherwise, they are impious and criminal."

These gloomy ages passed, however, and in the 7th and 8th centuries a certain revival of science took place in the Arab caliphates, the feudal states formed in the 7th century after the Arabs' conquests in West Asia, North Africa, and South-West Europe. The gorgeous courts of caliphs irradiated wealth and attracted poets, artists, and scientists. The frantic champions of the Moslem faith, who had finally ruined the ancient science, turned into admirers of this very science but failed to add anything new to what had already been known....

Works of ancient Greeks, and first of all of Aristotle, were translated anew, as in the times of the Roman emperor Augustus, and even academies of translation were organized. However, the Arabs had no adequate background to assimilate all that information, not to mention the ability to develop it further. One who perceived what the Greeks had known was considered a great scientist and taught others this 'lore'. The idolatry of teachers was then developed, as well as blind faith in authorities, a pedantic satisfaction with the order once established. The real phenomena were supplemented by imaginary and mystical ones.

Caliphates started to break apart under the pressure of Christianity in the 11th and 12th centuries, and the Arab philosophy had to fight for existence, implanting dogmatism and fanaticism. The name of Aristotle became disgraceful, scientists were despised and their works were destroyed.... That is why even the works of great Arabs were little known at that time and did not influence significantly the development of science.

A relative stability was soon established in Europe under the aegis of the Christian Church. Yet, it was not enough just to believe, one had to master the art of substantiating the dogmata of the Church. The Christian preachers, following the Romans and Arabs, turned to the works of ancient Greeks, Aristotle included, in the search for methods of teaching logic, dialectics (it was understood then as a skill of argumentation), and polemic. Thus a new type of scholar appeared, the scholastic, who recognized faith as the basis of knowledge and the Bible as the criterion of truth. These learned men tried to place the religious dogmata on a rational foundation. Sophistry* and the cult of authorities became the summit of 'science'. All points of argument were viewed from the positions of Christian ideas and canons. The explanation and investigation of the real world were replaced by

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* A deliberate use of wrong and false evidence (sophisms) in arguments and demonstrations

the explanation and investigation of ... works by Aristotle; the nature of angels, their speech, clothes, and digestion were 'studied' instead of the nature of man! It was missed, however, that the works of Aristotle, though not contradicting the dogmata of the Church, did open the way to the study of the world and development of exact sciences, i.e. to the separation of knowledge from faith. Scientific and pedagogical activities were revived, and the first universities were opened in Bologna, Padua, Salerno, Paris, and Oxford.

This scared the clergy so much that Aristotle's *Physics* and *Metaphysics* were prohibited between 1209 and 1215 since they "gave birth to heresy and could originate false doctrines yet unknown". The Inquisition had begun. At first it was the responsibility of bishops, but since 1232 the Dominicans were entrusted with this mission, and in 1252 they were licensed to obtain evidence by torture. Thus the begging order of 'Friars Preachers' (the vow was performed since 1220 to 1465) founded by a Spanish monk St. Dominic to fight heresy by sermons turned into the order of 'Lord's Hounds' eradicating 'heretics' on racks and by fires.

However, it soon became obvious that 'false doctrines' propagate even wider without Aristotle and cannot be controlled. Thus, the University of Paris was allowed to publish all 28 books by Aristotle, and after 100 to 200 years nobody could get a scientific degree, or title, or office if ignorant of these works.

When the gap between Scholasticism and reality became so wide that it was close to absurdity, an Italian theologian and natural philosopher, Thomas Aquinas (b. *c.* 1225, d. 1274), suggested the famous 'double-truth theory', i.e. the theological and philosophical truth. He propagated harmony of faith and reason and demanded that the 'truths of revelation' were always prior to the 'truths of reason'. This theory, Thomism, is popular in the Vatican even now.

Harmony, however, could not be maintained even under these conditions. Aquinas himself could not neglect experience, and a prominent scholastic, William of Ockham (b. *c.* 1285, d. *c.* 1349), suddenly declared experience to be the only basis of knowledge and rejected sophistical reasoning. He was anathematized for that and his works were burned.... Yet even this severe punishment could not impede thinking....

Roger Bacon (b. *c.* 1214, d. *c.* 1294), an Englishman considered by some to be a Frenchman, rejected the artificial constructions of the scholastics and advocated cognition of real nature. It is of special importance for us to mention his 'farsightedness' concerning energy. He managed to design by mere imagination almost all power machines which appeared 500 to 600 years later to devour impetuously power resources of the planet and increase entropy of the environment, and did this 150 years before Leonardo da Vinci. R. Bacon wrote: "I will tell about surprising things of nature and art in which there is nothing magical.... Water vehicles propelled without oarsmen can be constructed, as well as river and sea vessels controlled by a single man and moving faster than if they had a numerous crew. Chariots without horses capable of developing a very high speed also can be made ... it is possible to construct aircraft in which a man sitting in the middle of the vehicle operates bird-like wings with the help of a certain machine ... a device can be made to walk safely on sea and river bottoms...."

However, "...new ideas," said R. Bacon, "always meet opposition, even on the part of saintly and good-natured men wise in other issues." In fact, he was accused of heresy and witchcraft, removed as the head of the department office at Oxford, and imprisoned. Pope Clement IV freed him, but after the death of the pope, Franciscans again arrested Bacon who was hiding in France. The friars of the order which Bacon had once joined after the graduation from the university in order to continue his scientific studies could not forgive him his freethinking and sharp criticism of the ignorance and immorality of the clergy. All his works were banned and he himself spent ten years in a monastery prison. Having left prison at the age of 74, he could no longer propagandize 'seditious' ideas and died six years later forgotten by everybody....

Yet, Franciscans remembered him even 400 years later. Luke Wadding, a historian of this order, wrote about Bacon in 1682: "His mind was more astute than laudable. Such freedom to teach and think is not to be allowed.

There are individuals who think that they have learned nothing if they have not promoted science farther than it should be and have not suggested new ideas that come outside the orthodox doctrine."

Bacon, dissatisfied with Aristotelian physics, declared that there were three instruments of cognition: authority, thinking, and experience. Authority is insignificant if the verity of its arguments cannot be proved. In the process of thinking, a sophism can be distinguished from proof by testing conclusions experimentally. Thus, experimental science is the queen of sciences. Bacon said also that mathematics was the "door and key to science" and neglected scholastic arguments in favor of research into chemistry, astronomy, and optics, having turned, in fact, into the first naturalist of the Middle Ages.

Bacon rejected the Aristotelian theory of thrown bodies. This theory was argued also by prominent scholastics such as William of Ockham, J. Buridan (b. 1297, d. 1358), head of the University of Paris. Regardless of the official doctrine of 'secret' and 'hidden' inexplicable forces and categories, they developed an 'impeto' theory, the sources of which can be found in the works of ancient Greeks. Buridan mentioned a rotating top, a whetstone, or a sphere and asked: "How and where can air push them?" In his opinion, "...when the motive element moves an object, it imparts to the object a certain 'impetus', a force capable of moving this object in the direction similar to that in which the motive element moves the object regardless of whether it will be in an upward, downward, or circular motion. The higher the speed at which the motive element moves the object, the more the 'impetus' ... or impeto, the thrust." When a body falls, gravity, according to Buridan, continuously 'imparts' impetus to the falling body, thereby increasing its speed.

In this case we see a rejection of 'forced' and 'natural' movements, as well as a rejection of the 'abhorrence of a vacuum', and a revival of the notion of the expended 'force'. This was a confident declaration of the "increase in the velocity of falling bodies", and a vague hint at the connection between acceleration and the force (of gravity). Yet, even Buridan did not break relations with the dynamics of Peripatetics. In his doctrine heavier bodies fall faster than lighter bodies, since the "impetus imparted to them is greater". However, the impeto theory connects Aristotelian dynamics with the future dynamics of Galileo, as if bridging the gap between them. Hence the disintegration of the indefinite and polysemantic notion of 'force' into something external, acting on the body (later it will be called force), and something inherent in the moving body itself (later it will be called the kinetic energy of the body).

Renaissance. Gravitational, Magnetic, and Electric Forces

Scholastics did not know the Greek language and used mainly Arab reproductions of ancient classics, first of all those of Aristotle's works.

After the conquest of the Byzantine Empire by the Turks many scientists fled to Europe and immediately started to distribute works of ancient scientists in the original. Europe, which had yearned for fresh ideas and was bored by the clerical and scholastic yoke, Europe, in which the first shoots of capitalism with its practicalness, efficiency, lust for profit, and interest in discovery of new ways to enrichment had appeared, pounced on these works voraciously. It was then that the Renaissance came, the famous epoch when ancient cultural heritage and humanism were revived, the epoch of secular freethinking, the motto of which became the words ascribed to the great Voltaire: "...I don't approve of your ideas, but I will give my life for your right to defend them."

Nobody could have spoken about that time more explicitly than F. Engels did:

"Modern research into nature, which alone has achieved a scientific, systematic, all-around development, in contrast to the brilliant natural-philosophical intuitions of antiquity and the extremely important but sporadic discoveries of the Arabs, which for the most part vanished without results—this modern research into nature dates, like all more recent history, from that mighty epoch which we Germans term the Reformation, from the national misfortune that overtook us at that time, and which the French term the Renaissance and the Italians the Cinquecento, although it is not fully expressed by any of these names.... It was the greatest progressive revolution that mankind had so far experienced, a time which called for giants and produced giants—giants in power of thought, passion, and character, in universality and learning. The men who founded the modern rule of the bourgeoisie had anything but bourgeois limitations. On the contrary, the adventurous character of the time inspired them to a greater or lesser degree.... At that time natural science also developed in the midst of the general revolution and was itself thoroughly revolutionary; it had indeed to win in struggle its right to exist. Side by side with the great Italians from whom modern philosophy dates, it provided its martyrs for the stake and the dungeons of the Inquisition."

It should be noted that compass and gunpowder had already been known in Europe at that time, book-printing was invented in 1440, Columbus made his voyage in 1492-1493, the microscope was invented in 1590, and spyglass dated back to 1607.

Power engineering and machine building started to develop first in the form of watch mechanisms and mills, these being two material foundations "on which a preparatory work was done inside the manufactory to switch over to machine industry" (K. Marx) between the 16th and the middle of the 18th century.

Sun- and water clocks were replaced by first stationary mechanical clock which was a system of wheels and gears set in motion by weights. Between the 13th and 14th centuries these clocks were widely used in Europe as tower clocks and were considered one of the 'seven miracles of the world'. Later C. Huygens invented a clock-speed regulator, the pendulum. Then the pocket watch appeared in which power was provided by a coiled spring and the task of the pendulum was performed by a balance beam. The watch mechanism was the first to employ classical machine parts such as springs, gears, jaw clutches, ratchets, and so forth. So, research into these parts and development of their manufacturing technology started.

Whereas the energetic nature of clocks was hidden in the purpose they served, water- and windwheels rapidly crossed the sphere of grain-grinding devices and turned into a universal engine in mining, forge, metallurgic, and sawing industries. The mill brought about an inertial engine: a flywheel which served to extinguish the unevenness of rotation of waterwheels by way of accumulating energy. The water and wind engines became the starting point of research into elements of large machines.

Thus, the interest in practical science was revived, i.e. in science based on facts and experience and not on wordplay and mysticism.

Surprisingly, one of the first standard-bearers of this revival was ... Nicholas Krebs, the Cardinal of Cusa, Archbishop of Brixen (b. 1401, d. 1464). This son of a fisherman managed to reach a high position in the clerical hierarchy and wrote a treatise *On Learned Ignorance* in which he was bold enough to declare that there was no difference between terrestrial and heavenly phenomena, that the universe was infinite and had no center, and the Earth moved in the same manner as all other planets, the Sun and the Moon. He even formulated a kind of kinematic principle of relativity: "We feel motions only in comparison to a motionless point ... if one is on the Earth, the Sun, or any other planet, it will always seem to this individual that he is positioned in the motionless center, and all other things move...." Krebs considered experience to be the only criterion of truth (thus, in contrast to Aquinas, the truth was indivisible!) and even published a manual *On the Arrangement of Experiments* in which he described a multitude of experiments including an experiment to determine the time of bodies' fall, which played a most important role in the development of dynamics and was later carried out by Galileo (stones and pieces of wood were thrown from a high tower and the time of their fall was measured with the help of a water clock).

An artist, engineer, and scientist, Leonardo da Vinci (b. 1452, d. 1519), died in the year of Magellan's voyage around the world. Like Krebs, he believed that the universe was infinite and consisted of numerous noninteracting worlds surrounded by their own 'elements'. In his opinion, natural science was dead if deprived of experiments and mathematics, but experiment was only a stage in the study of causalities which formed the basis of all phenomena. If the cause can be discovered without experiment, there is no need for the latter, since "nature is full of countless causes which experience has never contained". He thought about the laws of nature, studied mechanics, and designed projects for the distant future (these included, independent of F. Bacon, his entire set of power machines). Da Vinci even composed a rather imposing panegyric to 'force':

"By force I mean a spiritual capability, an invisible potency, which is induced by motion by means of accidental external violence, placed and poured into bodies extracted and deflected from their natural state; while giving them an active life of surprising power, it forces all created things to change form and position, strives fiercely at the desired death, and propagates with the help of causes. Slowness makes it strong, and swiftness makes it weak. It is born because of violence and dies because of freedom; the greater it is, the sooner it is destroyed. It turns out vehemently everything which impedes its destruction, it desires to win, to kill its cause and resistance and by winning kills itself. It grows stronger there, where it meets the greater resistance. Every thing runs fervently from its death. If forced, every thing forces itself. No thing moves without it. The body in which it has appeared increases neither in weight nor in form."

This characteristic force, although vague but surprisingly capacious, versatile, and poetic, permits one to see the contours of all notions of energy, which were formulated much later. These include the notion of force proper, i.e. the causes of the change in the state of motion or that of rest of bodies; the notion of work, i.e. the product of force by the distance traversed by the point of its application; the notion of momentum, i.e. the product of force by the time of its action; the notion of energy, i.e. a measure of all forms of motion, and even that of entropy, i.e. a measure of energy degradation.... Yet Leonardo da Vinci went even farther in his reasoning-conjectures. Thus he wrote: "...every moving body moves continuously while the action of its motive element continues therein." In this case force comes out in the meaning of the Buridan's 'impeto', and there slips a hint at the principle of inertia of motion, i.e. of inertia*. He was already aware of the principle of equality of action and reaction (which Newton later made the third law of motion). He wrote: "A force is generated by the object acting against air, similar to that of air acting against the object." Moreover, da Vinci firmly believed in the principle of the conservation of ... energy! "Oh, you! The seekers for perpetual motion!" he exclaimed contemptuously. "What a host of shallow ideas have you launched into the world? Go to the gold-seekers!" (i.e. to alchemists—*G.A.*). He also professed the doctrine of mechanism, like almost all materialist scientists of that time, and considered mechanical motion to be the 'basis of everything' and explained phenomena such as sound, heat, light, magnetism, and so forth by various movements of the particles of matter.

These and many other quotations cited above bring us to the conclusion that the above-discussed notions and principles were finally formed much later probably not because humans had failed to think of them earlier, but because they were of no essential need, since they were required neither by science nor by practice. Thus, despite the existence of 'inherent' stimulus for their early development, the absence of an external stimulus delayed this progress for a long time.

A decisive blow against Scholasticism and clericalism was struck by great geographical discoveries, which also initiated a further evolution of the concepts of force, energy, and their material sources and carriers. As we know, astronomy revived earlier than other sciences, especially in German states where it occupied a major position up to the beginning of the 17th century. Yet neither Krebs, nor Leonardo da Vinci, nor the Germans G. Peurbach, J. Regiomontanus (Müller) and his disciple Walter were able to reject once and for all the Ptolemaic system; their observations and calculations only prepared the system's decline.

Only after the voyages of Columbus, who reached America in 1492, of Vasco da Gama, who discovered a route to India in 1498, and especially after that of Magellan,

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* The notion of inertia was first introduced by Jakob Bernoulli in the 18th century.

who made the first voyage round the world between 1519 and 1521, nobody could doubt that the Earth was a sphere rotating round its axis and moving in space. This not only eliminated the Ptolemaic system completely and delivered a blow against the Holy Writ but for the first time demonstrated on so large a scale and with assurance that *what is seen is not always that which exists*, i.e. the relativity of knowledge provided by sensory organs and the necessity of testing it by experience. Taken together, all this posed a major question to *energy* science: What forces, if not the divine ones, already doubted, move the world and preserve it in its natural state? Answering this question, that is the discovery of natural sources of active forces, meant 'heretical' infidelity to the Christian religion which had turned by that time into the master of not only the souls of men but also of their bodies, since the Church decided whether the 'heretic' must live or die, and decided always in favor of prison or death.

A new sensation, the discovery by Columbus of the western deflection of a magnetic needle, besides the eastern deflection which existed in coastal areas of the Mediterranean, punched one more hole in scholastic and theological 'sciences'. It meant that the Earth possesses unknown inherent forces which attract and repulse the magnetic needle, and this was in addition to forces which attract usual bodies!

Thus geographical discoveries made gravitational and magnetic forces a mystery of the age and ruined the foundation of principal theological scholastic constructions. It gave immediate birth to theories explaining and systematizing new experimental data. Thus the first scientific revolution in natural science began.

In 1543 a thinker, economist, physician, and statesman of Poland, Nicholaus Copernicus (b. 1473, d. 1543), decided at last on the eve of his death to publish his work "On the Revolutions of the Celestial Spheres", in which he laid down the heliocentric system of the world, which he had been developing for sixteen years. Copernicus did not share the ideas of Nicholas Krebs of Cusa and Leonardo da Vinci about the infinity of the universe. In his system the Sun was a motionless star positioned at the center of the Solar system. The Earth moves around its own axis and around the Sun. Planets move around the Sun. The two former motions had already been described by the Pythagoreans and Aristarchus of Samos (which Copernicus mentioned). To explain the change of seasons, Copernicus introduced the third motion of the Earth, i.e. a circular motion of its axis during the year around another axis crossing the center of the Earth and parallel to the axis of yearly rotation ('precession'); in this case two parallel and oppositely directed motions produce one circular motion of the Earth around the Sun. This was the kinematics of the motion of heavenly bodies in the new, anti-Ptolemaic, system. There were no forces in that concept, and thus the Lord's interests, and consequently interests of the Church, were not openly affected.

Yet it was impossible not to mention dynamics, i.e. forces. So Copernicus had to declare that gravity "is nothing but a natural desire to amalgamate into the form of a sphere, imparted by the Divine Providence to all bodies of the world". The sphere was a formal royalty of the 'Divine Providence', as was the Aristotelian 'natural motion' and the Pythagorean 'ideal form'. However, gravity acts further independently and regularly: terrestrial bodies gravitate towards the center of the Earth and thus neither the freely falling objects nor clouds can stay behind the Earth in the course of its motion, as Ptolemy had once stated when arguing the rotation of the Earth. Despite this discretion of Copernicus, the fact of the destruction of the clerical scholastic 'celestial mechanics', on which so many dogmata were based, was so terrible that the Church fought the Copernican system and its advocates for 300 years thereafter.

Yet even scientists, contemporaries of Copernicus, did not accept this system, so great were the forces of psychological inertia, of 'common sense' (really, how can people walk 'with their feet upwards'?), and fear of the Church. To reconcile the clerical 'theory' with facts, Tycho Brahe (b. 1546, d. 1601), a prominent astronomer, suggested an 'intermediate' system: the Earth is motionless with the Moon rotating around it, while stars move around the Sun as in the Copernican theory. Many liked this way out of a difficult position except ... Brahe's own assistant Johannes Kepler. The young scientist processed observations of his teacher made during long years of work and gathered a rich collection of facts in support of the Copernican system. Giordano Bruno and Galileo Galilei also became active advocates and popularizers of this system. G. Bruno (b. 1548, d. 1600) went farther than they all and developed the ideas of Nicholas Krebs of Cusa, Leonardo da Vinci, and the Copernican system into the idea of the infinity of the universe and a multitude of worlds existing without gods. For this he paid with his life and was burned in the Square of Flowers in Rome on the 17th of February, 1600 after eight years of prison and tortures to make him to renounce his convictions.

This very year the famous work of the British Queen's physician in ordinary William Gilbert (b. 1544, d. 1603) *De magnete, magneticisque corporibus, et de magno magnete tellure* ("Concerning the Magnets") was published in 1600, like a symbol of the indestructibility of human thinking, to make a gigantic step in the process of the study of other mysterious forces: magnetic and electric. Having rejected speculative inventing, Gilbert arranged more than 600 experiments and gave a detailed description of his results. This delighted Galileo enough to say 32 years later: "I praise, admire, and envy Gilbert. He developed exciting ideas on the subject which many men of genius had treated but failed to investigate with full attention.... Gilbert lacks only a mathematical background, especially geometry."

The physician in ordinary discovered a great number of natural and artificial magnets and found out that magnetic force is active at all points of the magnet's length—if crushed into pieces, a magnet turns into many small magnets—this force can be preserved and even increased if the magnet is fixed in steel fittings or covered by filings. He also discovered that magnetic force acts from a considerable distance through a steel wire and not through air (as it had been believed before) as well as the magnet's property to induce magnetism in other bodies, i.e. magnetic induction, but did not realize and estimate the full importance of this most notable discovery.

Having bravely rejected the thousand-year-old opposition of the terrestrial world to the heavenly world, Gilbert proclaimed that the Earth is a large magnet and proved it experimentally, with the help of an iron magnetized ball which, he assured, should act on the magnetic needle in the same manner as the Earth does. He believed that the geographical poles do coincide with the magnetic poles, but accounted for the deflection by the absence of magnetic properties in sea and ocean waters and the unevenness of dry-land distribution. He demonstrated that iron can be magnetized directly by the Earth. (However, another Englishman, Robert Norman, had already discovered this 20 years earlier and established that the point which attracts the magnetic needle is positioned in the Earth.)

The property of amber to attract, if rubbed, light objects like straw, for example, was known from ancient times. Gilbert discovered that diamond, sapphire, amethyst, opal, glass, resins, sulphur, rock salt, and other substances also possess this property, or electric 'force' (the Greek word for 'amber' is *elektron*). They attract almost all solid bodies. On the other hand, metals, ivory, pearl, agate, and emerald cannot be electrified. He investigated the influence on the electric force of heat, wind, air humidity, water, alcohol, and even ... olive oil!

However, Gilbert failed to develop a theory of the discovered phenomena farther than his predecessors had done, the mechanists at best. Thus he did not consider the idea of Thales, who believed the magnet to have a soul, to be an absolute absurdity. In Gilbert's opinion, magnetic force is a property of material acting on certain bodies, while electric force generated by friction acts on many bodies. Gilbert defined gravity as a force of mutual attraction of the bodies of one planet, in contrast to the Peripatetics' idea of it being gravitation towards a certain point in space. Magnetic force acts between planets, making them rotate near one another without approaching each other.

After the publication of Gilbert's work, the interest in agnetic and electric phenomena increased significantly. A lot of papers and treatises were published on this subject, although they did not contain anything essentially new even despite the attempts to measure magnetic force with the help of scales.

Of principal importance were only the experiments of the Magdeburg burgomaster Otto von Guericke (b. 1602, d. 1686), who made something similar to the first electrostatic machine. He took a spheric flask made of glass, filled it with melted sulphur, and broke the glass after the sulphur had solidified. He fixed the so manufactured sulphur sphere 'of a child's head size' on an axis and electrified it in rotation by rubbing the palm of his hand against it. This experiment demonstrated surprising phenomena: (1) a bit of fluff attracted by the sphere was repulsed after contact, while other bodies (nose, for instance!) attracted this very fluff, after which it was again attracted by the sphere; (2) a linen thread connected to the sphere attracted (or repulsed) objects with its free end like the sphere itself; (3) the sphere electrified in darkness generated 'electric light'; (4) a bit of fluff fixed on a thread followed the motion of the electrified sulphur sphere around it, but faced the sphere always with one and the same side.

Neither Guericke himself nor his contemporaries could realize the real importance of these phenomena which were in fact great discoveries. The first implicated the discovery of two electric charges; the second was that of electric conduction (these discoveries were officially registered by an Englishman, S. Gray, in 1729, and a Frenchman, C. Du Fay, in 1734); the third was luminescence, and the fourth (following Gilbert) 'almost' electromagnetic induction.

Thus, man, influenced by irrefutable experimental data, took for the first time liberty to trespass on the dominions of the Lord and the Church by having investigated into the natural origin of gravitational, magnetic, and electric forces and, consequently, the energy sources which generate these forces. This was an event of cardinal importance which brought about a revolution in 'celestial mechanics', which could not have failed to induce a reconstruction of terrestrial mechanics. And, indeed, first of all, notions connected with motion and active forces were revisioned. At that time notions such as 'force', 'work', 'momentum', and 'energy' started to be formulated intensively.

Celestial and Terrestrial Forces

As has been mentioned above, gravitational forces interact between the bodies of one planet (according to Gilbert), and magnetic (or electric, according to Guericke) forces interact between different planets. Yet when developing the Copernican heliocentric system, Johannes Kepler (b. 1571, d. 1630) not only improved the kinematics of planetary motion but for the first time viewed gravitational and magnetic forces as identical. Thereby he contributed substantially to the evolution of the general notion of 'force' and then such notions as 'work' and 'energy'. Kepler replaced the circumferences of the Earth's and planets' rotation around the Sun by ellipses and introduced elliptical motion at a constant 'sectoral velocity' (i.e. the radius vector of a planet describes equal areas at equal time intervals) instead of uniform circular motion. These two Kepler's laws together with the third law, i.e. the squares of the periods of revolution of any two planets of the Solar system are proportional to the cubes of their mean distances from the Sun, had provided the basis on which modern celestial mechanics was built.

Having established the elliptical motion of planets, Kepler had to reject the kinematics of uniform motion, which Copernicus had borrowed from Ptolemy, and search for the reasons that increase (or decrease) the velocity of motion, i.e. acceleration*. According to Aristotle, whose doctrine still influenced Kepler, nonuniform motion must cease when force is exhausted. In search of its origin in the real world, Kepler raised the 'Divine Providence' above the Sun and made the 'animate force' of the Sun (that is, in modern terms, the store of energy contained therein) a carrier of motive forces, harmony, and light. The Sun is a limited sphere positioned at the center of the universe. The 'animate force' supports the rotation of the Sun around its own axis as a result of which the Sun carries along other planets while producing around itself 'force threads' (almost the same lines of force which were introduced by Faraday 200 years later). In Kepler's theory, the motive force of the Sun is identical to the

* At that time this term was not used.

magnetic forces propagating in a plane, and hence, similar to the latter, is inversely proportional to distance. This was an explanation of the elliptical 'automotion' of planets around the Sun at the velocities inversely proportional to the distance from it. This is a most clear and explicit expression of the relation of force in its proper meaning to acceleration, which Newton would later make one of the three laws of mechanics. However, Kepler failed to comprehend the principle of inertia.

Similar to Gilbert, Kepler considered gravitation to be the force of attraction of single parts to combine, in contrast to Aristotle's idea that they strived to a certain 'natural place'. Thus, the single parts move by the shortest distances to combine. From this point on Gilbert's and Kepler's views part ways. Gilbert assumed that single parts of a heavenly body are attracted to its center (i.e. still to a 'place'!), while Kepler believed them to be attracted to one another. According to Gilbert, the forces of attraction to the Sun, stars, and the Earth are different for each heavenly body, while according to Kepler, gravitational forces are similar everywhere, and gravitation becomes a universal characteristic of substance. All bodies—elements of substance—are connected by mutual attraction. This is, in fact, the law of universal gravitation, the quantitative expression of which Newton once again would provide later. According to Kepler, space is filled with some ether substance, of which comets and new stars are formed as a result of the cosmogonic condensation processes. Light is a weightless matter, which propagates rectilinearly in all directions and at an infinite speed; the force of light (one more 'force'!) decreases inversely proportional to the square of the distance from the source. Kepler's new-knowledge-based conjecture about the material nature of light was an extension of the theories of ancient atomists and Aristotle, and anticipated a whole epoch in physics, i.e. that of 'imponderable' matter, which would come only 120 to 150 years later.

Thus celestial mechanics was filled with new contents, thereby generating concepts of various types of 'forces' including that which would later give rise to the evolution of the notion of energy. Simultaneously, a lot of observations contradicting the theoretical canons of the

Peripatetics were being made on Earth. The principal elements of the Peripatetics' mechanics, i.e. the dynamics and kinematics of dropped bodies, began to appear more and more unnatural. According to the doctrine officially accepted at that time, a stone (or a projectile) should first fly horizontally performing the 'forced' motion imparted to it, then proceed to assume a mixed circular motion, and at last fall down 'naturally' in a vertical direction.... Not many dared to argue this cabalism, although anyone could see that no thrown body moves by such a trajectory. But at last the prominent Italian mathematician Niccolo Tartaglia (b. *c.* 1500, d. 1557) declared publicly that the trajectory of a body flying in any but a vertical direction can only be a curve and "contains not a single absolutely straight portion". Yet he also did not dare to reject the theory of natural and forced motion and accounted for the curvilinear trajectory of bodies' flight by the continuous 'mixing' of these types of motion. Thus, according to his theory, the maximum flying range of a body was reached when these motions were 'in equilibrium', and the angle of departure to the Earth's surface was 45°.

Tartaglia's disciple Giambattista Benedetti (b. 1530, d. 1590) criticized the official mechanics more openly. He declared that the motion of a thrown stone occurs not because it is pushed by air, but owing to the 'impetus' imparted to the stone by the force of the hand, while air does nothing but impede the motion. Thereby Benedetti, in essence, proclaimed the principle of inertia of motion, although this was but a vague hint at the latter. Proceeding from this principle, he renounced the Aristotelian theory of bodies' fall and suggested a directly opposite theory of his own. Benedetti proved his idea with the help of a simple imaginative experiment. He divided the falling body into several parts equal in weight and volume and declared that the velocities of their fall would be equal since there are no reasons for this to be otherwise. He accounted for the acceleration of the bodies' fall by the increase in the above-mentioned 'impetus' resulting from the continuous action of a constant force and not from the increase in weight as scholastics declared. This was the first open, explicit, and well-grounded demonstration of the independence between the time and velocity of a fall and the weight of bodies. The principle of inertia of motion enabled Benedetti to suggest the existence of centrifugal force (inertia): if a body performing a circular motion is not fixed, it will move away from the center of the circle by a tangent like "mud flying off the coach-wheel". Furthermore, Benedetti investigated the equilibrium of fluid in communicating vessels and discovered 70 years earlier than Pascal and one year earlier than Stevin (Stevinus) the 'hydraulic paradox'—the equal pressure of the fluid at the base when the heights of the fluid columns are equal is independent of the form of the vessel. However, all these clever ideas were not welcomed by contemporaries as they deserved and resulted only in the persecution of Benedetti.

The aristocrat Guid ubaldo marquis dal Monte is famous not only for his translations of Archimedes and many-year patronizing of Galileo. In his *Mechanics*, he discussed simple mechanisms such as the lever, wedge, screw, block, winch, and pulley block, and for the first time abstracted the notions of 'weight' and 'force'. Instead of them he used the two identical forces which he understood as pressure or attraction measured by pounds and in each case properly directed. He also introduced the notion of 'moment of force' (in Latin *momentum* means 'movement') as the product of the magnitude of the force by the distance from the center of rotation along the perpendicular dropped from this center onto the line of action of the force. This notion has been widely used in mechanics from that time up to the present and makes a lot of problems much easier to solve.

"The Elements of Equilibrium" by Simon Stevin (b. 1548, d. 1620) was published in 1585. Historians of science consider it to have contributed significantly to the establishment of classical mechanics, but at that time the public was not very much aware of this treatise because the author neglected the obligatory Latin language and wrote his book in Dutch. Simon Stevin came to the idea (independently of Leonardo da Vinci) of the absolute impossibility of perpetual motion. Moreover, he not only suggested a theory but also applied it to practical problems of statics. Only 185 years later the Paris Academy of Sciences passed a decision not to consider projects for perpetual motion machines, and only 260 years later the principle of conservation of energy evolved from this very principle! Yet Stevin engaged this principle to prove the law of the equilibrium of a body on an inclined plane. He treated the equilibrium of a closed bead-like chain positioned on a certain object, the cross section of which forms a right-angled triangle with a horizontal hypotenuse. If the force acting on this object positioned on an inclined plane were equal to the object's weight, concluded Stevin, the heavier portion of the chain, positioned on the long leg, would roll down and pull all the other portions along with it. The chain would then move perpetually, but this never occurs. Thus he arrived at the conclusion that the force which makes the body roll down the inclined plane does not equal the weight of the object. It is as many times less than the weight as the height of the plane is less than its length.

This very model helped Stevin to establish the principle of addition of simultaneously acting forces and the principle of decomposition of force into two component forces perpendicular to each other. Proceeding from this principle, Stevin suggested a new formulation of the Archimedian principle: any particle of a motionless mass of fluid should be in a state of equilibrium; if it were not true, this particle would start moving and other particles would follow it, resulting in perpetual motion, which is an absurdity. Independently of Benedetti, although a year later, Stevin formulated more clearly and explicitly the 'hydrostatic paradox'—the equality of forces of a fluid's pressure at the base of vessels of any form when the heights of the fluid columns are equal.

Thus the notion of force was gradually expanded and more frequently divided into force proper and 'forces': energy, work, and momentum.

"Let Us Laugh, My Kepler, at the Stupidity of Men!"

Not long before the great Galileo Galilei (b. 1564, d. 1642) was born in Pisa into the family of a Florentine impoverished patrician, Europe, despite a certain progress of reason, had lived a life of naive unreality, charlatanry, and scientific research. Aristocrats pounced on the four-volume *Magia naturalis* ("Magic") by 20-year-old Giambattista della Porta, which gave instructions on how to determine whether a maiden is really a virgin with the help of a magnet and how to make a lamp which turns the heads of guests into horseheads. However, the second twenty-volume edition of "Magic" published thirty years later contained also some 'scientific' facts. These included, for example, a declaration that magnetic properties of a pack of filings vanish if the filings are scattered and mixed.... This edition, however, was not much in demand....

The activities of Galileo started at a time when the Peripatetics enjoyed the full support of the Catholic Church, occupied the major positions in official science, and surrendered only when dead. Yet their struggle against the new benefited this very new. Being forced to perform experiments in support of Aristotle's theory, they got results which refuted this very theory and thus introduced experimental research technology, which was of no minor importance. The major battlefield was still the systems of the world. Galileo won worldwide popularity by supporting the heliocentric system in this fight ("Dialogue Concerning the Two Chief World Systems—Ptolemaic and Copernican", 1632). Yet his final work "Dialogue Concerning Two New Sciences" (1638) was publicly acknowledged and appropriately evaluated only at the end of the nineteenth century.

Galileo's contribution to mechanics and strength of materials proved even greater than that to astronomy! His criticism of Ptolemy was not so important for astronomy as for discrediting the erroneous ideas of Aristotelian dynamics and working out the new ones instead of them. This was even more true since Galileo himself was in error in many aspects of astronomy (his system of the world repeated the already obsolete system developed by Aristarchus of Samos; he did not accept the elliptical motion of planets, although he shared the ideas of his friend Kepler, he supported the weakest part of the Copernican theory, e.g. the notion of cosmic inertia, and so forth). There is a legend that 19-year-old Galileo noticed that icon-lamps in the Pisa Cathedral, which were different in weight and size but supported by equal lengths of cord, were swaying from side to side in time, i.e. isochronously. This observation enabled him to formulate the principle of the isochronous oscillations of a pendulum at low amplitudes and, even more importantly, to conclude the erroneousness of the Aristotelian principle of the velocity of bodies' fall being proportional to their weight, since the icon-lamps moving from their extreme to medium positions did fall, although held by supporting cords, at the identical velocities in every case.

Already in his early work "On Motion and on Mechanics", Galileo declared publicly and proved experimentally (he dropped different objects from the inclined tower of the famous Pisa Cathedral) that the velocity and time of fall of all bodies falling from the same altitude should be equal (naturally, if the cross sections of the bodies are small and air resistance is low). In the same treatise he rejected the Aristotelian 'force of lightness'. If a piece of wood floats in water and falls down in air, there is no 'force of lightness'—all bodies are 'heavy' and the direction of their motion depends only on their specific weight compared with that of the environment. Finally, he refuted the Aristotelian principle that "nature abhors a vacuum" and the explanation of the motion of bodies by air-pushing based on this principle. To prove the idea, he used the same example as Buridan did, i.e. a sphere rotating around its axis with no place left for air to push it.

The Peripatetics instructed that cold and heat were different properties of matter, which were mixed therein and thus immeasurable. Yet Galileo declared that cold was not a positive property but the mere absence of heat, thus it was contained not in matter but in a sensitive body. Heat was by nature a "multitude of small particles of this or that form moving at this or that velocity, which meet our body and penetrate it with great agility; their contact felt in the course of their penetration through our tissues is that very action which we call heat...". This could have been an almost mechanistic idea of heat if the above-mentioned particles had been termed molecules, yet Galileo considered them to be particles of a special substance, i.e. fire, which is identical to the ancient Greek's idea. This definition of heat inspired Galileo to measure the 'degree of heat and cold', for which purpose he invented the first thermometer—'thermoscope'. This was a flask the size of an apple with a very long thin neck submerged into a cup filled with water. If the flask was heated by hand and then lowered into the cup, the water raised up the neck. This 'thermometer' found wide application in various spheres including medicine.

Soon Galileo invented a telescope which helped him to make a number of astronomic discoveries irrefutably corroborating the Copernican system. The Church and advocates of official science declared the discoveries to result from "defects of the telescope". This made Galileo write to his friend: "Let us laugh, my Kepler, at the stupidity of men!" Galileo's "Dialogue Concerning the Two Chief World Systems" was published when he was 68 years old. He attacked the Peripatetics with long-reserved passion: "Some individuals arrive at hasty conclusions, fix this or that idea in their minds, and then hang onto it stubbornly as if it were something of their own or acquired from responsible persons and there is no way to eradicate it from their heads." One of the personages of his book laughs at such men: "If we discard Aristotle, who will guide us in science?" The "Dialogue" impressed Europe by a brilliant demonstration of the Copernican system and invoked the rage of the Inquisition. Under the pressure of this holy organization, Galileo signed on June 22, 1633 his renouncement of that system, thus paying an enormous price for his life and freedom necessary to finish his work. A weak, almost blind and deaf Galileo continued his tireless labors. In 1638 his "Dialogue Concerning Two New Sciences" was published in Holland, the first bourgeois republic, and this work finally ruined Aristotelian physics.

Galileo died on January 8, 1642. Besides his deathbed stood his son, his daughter-in-law, his two disciples—Viviani and Torricelli—and ... two guards of the Inquisition.

Several centuries later, already in modern times, the Church declared the prosecution of Galileo a 'mistake', and Bruno was even canonized.... This was a gesture inspired not so much by good will as by the desire to benefit from science and to support its own shaken authority.

The "Dialogue" contains in this or that form almost all major notions and principles of mechanics directly related to the subject of our discussion.

The accumulated scientific and practical data stimulated Galileo to analyze anew the motion of a stone thrown upwards. He arrived at the conclusion that the "imparted momentum is eliminated by the decline of its initial excess over the weight of the body". In Galileo's theory, the Aristotelian 'natural' fall of a stone turns into a forced fall induced by gravity. On the other hand, the 'forced' uniform motion of a body under the action of a certain pushing force of air turns into a natural motion performed with no force applied. Force is required only to alter this motion. Thus, uniform motion occurs by inertia. Galileo widely applied the principle of inertia, although his was a 'cosmic' idea similar to that of Copernicus: the motion of a body on which no forces act is a circular motion. Straight uniform motion is impossible since it is infinite, and in nature nothing can pursue an objective which cannot be reached (this is from Aristotle!). To estimate uniform motion, Galileo introduced the term and notion of velocity (not applied in ancient mechanics), although he did not care to provide a precise definition and was satisfied with a mere comparison of the velocities of two bodies.

Having noticed the unevenness of the bodies' fall, Galileo introduced the notion of uneven motion, its true (instantaneous) velocity, and the 'rate of velocity change', i.e. acceleration. Galileo assumed the latter to be a constant value for all falling bodies (the term 'acceleration' came into use much later). Galileo established theoretically that the velocity of a falling body was directly proportional to time (he believed initially that it was proportional to the distance traversed, but then corrected his error), while the distance was proportional to the square of time. His reasoning was as follows.

If in the first second the velocity imparted to the body by gravity is $\omega_1 = g \times 1$ m/s, then by the end of the next second it will be $\omega_2 = g \times 2$ m/s, by the end of the third second it will be $\omega_3 = g \times 3$ m/s, and by the end of the τ second it will reach the value $\omega\tau = g \times \tau$ m/s; here g is the rate of velocity alteration, or the acceleration of free fall (equal to 9.81 m/s²). Since the mean velocity of the body during the first second is $\omega_{1m} = 0.5 \times (0 + g)$ m/s and the distance traversed $l_1 = 0.5 \times g \times 1 \times 1$ m, the mean velocity in two seconds will be $\omega_{2m} = 0.5 \times (0 + 2g)$ m/s and the distance traversed $l_2 = 0.5 \times g \times 2 \times 2$ m, the mean velocity in three seconds will be, consequently, $\omega_{3m} = 0.5 \times (0 + 3g)$ m/s and the distance traversed $l_3 = 0.5 \times g \times 3 \times 3$ m. Thus, the distance traversed in τ seconds will be $l\tau = 0.5g\tau^2$.

Galileo tested these dependences thoroughly by experiments. These were carried out with the help of a bronze ball* launched along a chute cut into an inclined plane and covered with parchment to decrease friction. Time was measured by the quantity of water flowing out of a pail through a thin pipe. Yet even this technique provided the precise value of the acceleration of free fall, i.e. $g = 9.81$ m/s².

Similar to Aristotle, Galileo compared different action of the equal gravity both of a falling body and that exerting pressure. He arrived at the conclusion that the weight of a falling load used tohammer piles to an equal depth should be less than the weight of the pile by several times but failed to explain this phenomenon. These and similar observations resulted 50 years later in the division of forces into 'animate' and 'inanimate', and in the famous argument about two measures of motion. The term 'force' was not yet clearly defined by Galileo and was used together with terms such as 'moment', 'momentum', 'work', and even 'energy', being interpreted differently for various problems. Yet Galileo measured the action of force by the velocity imparted to a body at a given time, i.e. by acceleration, although he was unaware of the notion of mass and thus failed to correlate these values correctly.

However, Torricelli modified Galileo's idea of 'moment' in 1644 and replaced the weight of a body by an 'amount of matter', a measure of matter's inertness which is actually its mass. According to Torricelli, the amount of matter determines the "reaction of a body

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* According to other data, with the help of an ivory ball.

against the push; since matter is dead by nature, it serves only to impede and resist the acting force. Matter serves only to house force, moment, and momentum". Yet, similar to those of Galileo, the above-mentioned terms lack a clear definition.

In his research Galileo engaged the principles of superposition of motions, independence of the action of forces, relativity, inertia, probable distances traversed (probable velocities), and others. The last principle is of special importance since it postulates the conservation of work. Applied to the lever, this principle was known in ancient times as the 'golden rule of mechanics' (the more you gain in force, the more you lose in distance). The principle was operative with Archimedes, Hero, Stevin, and other scientists of that time. Yet Galileo was the first to formulate this rule as a general principle of statics: "When equilibrium is reached and both bodies come to rest, then moments, velocities, and their disposition to motion, i.e. space intervals which they would travel in equal times, should relate to each other inversely proportional to their weights...." The final definition of this principle was given by J. Bernoulli in 1717.

Thus Galileo discredited the mechanics of the Peripatetics, established a number of correct regularities and notions, and initiated the final formation of this branch of physics.

The progress in this area was promoted by the increasing public interest in experimental-technical research, for which purpose special scientific societies were founded, which became the prototypes for the future academies of sciences. Thus the Accademia Secretorum Naturae (the Academy of Secrets of Nature) was opened in Naples in 1560 (however, it was soon accused of 'witchcraft' and closed), the Accademia dei Lincei (the Academy of Lynx-eyed), of which Galileo was a fellow, was founded in Rome in 1603, the Royal Society of London for Improving Natural Knowledge was formed between 1645 and 1660, the Accademia del Cimento (the Academy of Experiments) was organized in Florence in 1657, and l'Académie des Sciences (the Academy of Exact Sciences) was established in Paris in 1666.

This gave rise to the publication of collections of works and the exchange of findings between scientists. Science was organized in a way which helped it to pursue its major objective: the development of a real and comprehensive system of knowledge about real nature. That purpose required a 'project', that is methods of research into the world, without which further progress was impossible as was the further formation of scientific notions....

Triumvirate

Hail, muses! Hail, reason! In song let us praise them!
Thou, bright sun of genius, shine on!
Like this ancient lamp that grows dimmer
And fades with the coming of dawn,
So false wisdom pales at the first tiny glimmer
Of true wisdom's ne'er-fading light....
Live, radiant day! Perish, darkness and night!

*A. S. Pushkin**

Falsely Directed Efforts Multiply Errors

In the 17th century natural science broke at last the chains of religion, Scholasticism, official dogmatic philosophy and became grounded on a solid foundation of experiments and mathematics, i.e. the establishment of quantitative dependences. More thorough research into separate objects and natural phenomena started, although their interrelation and interaction were not studied, which was a metaphysical approach. The resulting achievements of science by far exceeded everything done before, and the scientific revolution continued in the 17th century.

The new philosophy, spontaneously formed and materialistic by nature, was closely related to natural science and thus had similar features. Its major objective was to develop rational scientific methods and, consequently, notions including those related to energy.

When it is said that Galileo initiated the organization of physics into an independent science, it is implied that it was not his discoveries that were so important but the new mode of reasoning which he introduced into the process of cognition. The experiment was not an end in itself. It only served to crown the evolution of an idea, to establish either its correctness or falsity. Sensible experience, an initial hypothesis, the mathematical development of it, and at last—a rationally arranged experiment—these were the stages of scientific research to which Galileo logically adhered. He proceeded from the idea

* Translated by Irina Zheleznova.

that the book of nature "was written in the language of mathematics, the letters of which are triangles, circles, and other geometrical figures, without the help of which man would fail to comprehend the book's message...".

The new philosophy and scientific methods were developed by the Englishman Francis Bacon (b. 1561, d. 1626) and the Frenchman René Descartes (b. 1596, d. 1650), although they advocated different methods which had been already developed in ancient Greece and spontaneously applied by many scientists. Bacon originated reasoning by induction, which is the progression from the results of particular experiments to general conclusion, and Descartes, being a mathematician, introduced deduction, i.e. the progression from general ideas and theories to particular ideas and conclusions which are characteristic of mathematics. Both of the scientists did not deny the advantages of each other's method but each gave priority to his own.

Bacon was the first to notice that old theories of logic did not correspond to new objectives not only because they cared little about knowledge of the laws of nature but also because *notions* which they represented "were erroneously separated from things". Hence an adequate method to form notions is required, since methods designed to operate on ready-made notions cannot correct principal errors committed in the course of the formation of these notions. *Falsely directed efforts multiply errors.* This has been demonstrated above.... Bacon assumed that induction could solve this problem as well as others. K. Marx and F. Engels called Bacon the real founder of English materialism and experimental science of modern time.

Bacon was born into the family of a lord keeper and studied law in Cambridge and Paris. In 1604 he was appointed to the Private Council, in 1615 he became an attorney general, from 1618 he was a lord chancellor, and in 1621 he was titled baron Verulam. At that point, however, his career was halted. That very year he was accused of corruption and removed from all offices, deprived of titles, imprisoned in the Tower, and heavily fined. Yet the King soon forgave his favorite, although he never let him resume public activities.

In 1620 the lord chancellor of England published the

Novum Organum ("New Organon"), in contrast to the *Organon* by Aristotle ('organon' means 'tool', 'instrument'; in this case, an instrument of cognition), in which he attacked Aristotelian philosophy and logic and suggested instead of them his own method of reasoning for natural sciences. Bacon was able to understand better than others, from the height of his official position, that capitalism turned manufacture into mass production, and science had to become a daily occupation of many men with average talents to meet the increasing requirements of production. This could have been the major reason why he concentrated on the development of a method which would "leave room for the acuity and power of talents while keeping them almost in balance". Bacon associated the new scientific method with new technological achievements. "The bare hand and reason left by itself, he wrote, do not have any significant power. The action is carried out by instruments and devices required not less by reason than by the hand. As the instruments of the hand induce or direct motion, so the instruments of the mind command reason or warn it." His method was to become an instrument of the mind in science.

Bacon instructed that reason should "purify experience" and derive therefrom laws of nature. In his opinion, either empiricists or dogmatists had been the makers of science so far. Empiricists, like ants, only collected and used the collected items. Dogmatists started directly from reason and extracted ideas out of their own bodies like a spider spins his web. The right way is only that of a bee which collects material by flying from flower to flower in gardens and fields but processes and digests it in her own way. This very processing should be performed by the method of induction, that is by a gradual progression from details to minor axioms, then to medium ones, and at last to the most general ideas. However, experiment should be the only criterion for the validity of results.

Bacon thoroughly developed the 'technology' of inductive reasoning. Yet he warned that the smooth progress of inductive reasoning could be impeded by errors of reason—'idols'. *Idola Tribus* ('idols of the tribe') depend on the ability of the human intellect to see more order in things than there is in fact. *Idola Specus* ('idols of the cave') are conditioned by habits, upbringing, and education. *Idola Fori* ('idols of the market place') stem from the wrong use of words. And at last, *Idola Theatri* ('idols of the theater') result from invented theories which are classified as sophistry, empiricism, and superstition. For example, Bacon related the Aristotelian theory to sophistry. This analysis of the difficulties of intellectual activity has not lost its vigor even in modern times—psychologists deal with it even today. To help the scientists, Bacon composed 24 groups of 'prerogative instances'. One of these, e.g. 'crucial instances', was safely established in science as 'crucial experiments' which Newton introduced to choose the one best corresponding to facts from competing theories.

According to Bacon, only elemental matter is the 'cause of all causes' including the cause of 'specific forces and actions'. Yet Bacon was too concerned with the development and propagation of this method to care for experimental research, including that which investigated notions such as 'force', 'work', and 'energy'. However, he influenced significantly the formation of the above-mentioned notions. Thus, Newton, who had contributed greatly to the solution of this problem, accepted only the inductive method.

To demonstrate the efficiency of Bacon's method, we may take his definition of heat. After a long chain of reasoning, grouping of facts into tables of positive and negative 'instances', and then comparing them in the table of 'degrees and comparisons', Bacon arrived at the conclusion that "the form of heat is a violent, irregular motion of particles". Since a body giving off heat does not decrease in weight, Bacon reasoned, there can be no transition of substance in the course of heating, and if all bodies can be heated by friction, then the existence of any 'thermal substance' (particles of fire, or later 'thermogen') is impossible. Almost 230 years later, after having wandered a lot (under the influence of the 'idols of the theater') in the thermogen kingdom, scientists discovered this definition and modified it according to the new achievements of science. Other predictions of Bacon were also surprising. These included the hypothesis of the finite velocity of light, his project of a series of experiments to study gravitational forces, and so forth.

Yet even Bacon accepted deduction as the basis of mathematics. It is thus not surprising that René Descartes, a prominent mathematician, the founder of analytical geometry, became an advocate of the deductive method. But Descartes not only developed and popularized his own method. On the basis of it he constructed the latest comprehensive natural-philosophical system of the world, which seemed to connect the indivisible science of the ancients with the new science formed after the 17th century to bridge the gap of many centuries of the absolute power of religion and Scholasticism.

The Russian physicist N. A. Umov wrote that Descartes' great service to history was that he had created "a new scheme to solve problems of knowledge ... in the fight against scholastic theories". "Thinking humanity already faced not separate facts contradicting conventional views and having no connection with the new ones— it faced a real and vigorous mode of exact knowledge which was inferior to the old doctrines neither in force nor in scope and precision."

Descartes (his Latin name is Cartesius) did not start out as a philosopher. This scion from an old noble family graduated from a Jesuit college at the age of sixteen and took an army commission. He lived a usual loose and dissipated life in the intervals between maneuvers and battles. But, according to his own words, November 10, 1619 was a very cold day in Bavaria and he spent all of it in his room, watching lightning and listening to thunder, when a sudden idea flashed in his mind. The idea was to work out analytical geometry and apply mathematical methods to philosophy. He wrote: "I ... had to discard as absolutely false everything which could induce the slightest doubt. But what is doubtless? From where should I start? Where is that truth which is so solid and veritable that even the craziest insinuations of skeptics would fail to discredit it...?" Descartes found this truth in the principle *cogito, ergo sum* ('I think, therefore I am'). His reasoning was as follows: if I exist and feel the surrounding world, so this world exists as well as I myself. But then God should undoubtedly exist, if he did not, who made all these things? It was God who created a certain amount of matter and momentum (this automatically leads to the 'laws of conservation'). Then he continued: "Yet it is undoubtedly better for the study of plants and man to follow their evolution from their seed than to examine them as they were created by God in the course of his making of the world. If we are capable of discovering certain principles, simple and easily understood, which can help to trace the origin of stars, the Earth, and all that we find in the visible world, like we trace the evolution of the seed, although we knew that these things had a different origin, this would enable us to explain nature much better than if we described only the existing things. I believe that I have discovered such principles and these I will communicate in brief." Thus Descartes managed to preserve God and show the way to the cognition of nature....

On that cold Bavarian day when the young rake decided to start a new life, he was a contemporary of the 58-year-old lord chancellor of England F. Bacon, and the 55-year-old Italian 'heretic' Galileo Galilei. The sudden interest in philosophy made him retire for two years to think in solitude. However, he failed to stay aloof from political and military conflicts and passions of the time and only in 1624, after the end of the Czech period of the Thirty Years' War (1618 to 1648), he settled in Holland and made scientific work his sole occupation. His mathematical works "Rules for the Direction of the Mind", "Discourse on Method", "Principles of Philosophy", and others won him the recognition of progressive scientists and angered clergymen and scholastics. In 1649 he moved to Stockholm, on the invitation of the Swedish Queen, where he died of pneumonia having not survived his 54th year.

Descartes defined the final objective of knowledge as the rule of man over the forces of nature, which was very much like Bacon's idea. But in contrast to Bacon, according to the latter's classification, Descartes was that very spider-scientist who "starts directly from reason and extracts ideas out of his own body like a spider spins his web". Descartes denied all doctrines, dogmata, and authorities, especially that of Aristotle, and believed "only that which is evident". His method of deduction consists in the decomposition of compound sensations into components until the latter turn into simple and clear 'ideas'. Like Euclid in his geometry, he introduced several axioms on the basis of which he constructed a system of conclusions which he believed to be no less reliable than the initial axioms. Matter, created by God and immutable on the whole, suffers, according to Descartes, "certain alterations of its portions" characteristic of nature. He termed the rules which determine these alterations laws of nature and declared his objective to be the establishment of these laws. But all changes treated in his theory were mere mechanical transitions of matter, the only property of which was "continuity endowed with form". Descartes proclaimed: "Give me matter and motion and I will make the world!" He did make a world by having developed a system of his own. Even animals are sophisticated mechanisms in his theory, and man is the combination of a mechanism and a 'discontinuous soul', the nature of which differs from that of the body. Yet he neglected the best achievements of mechanics of that period, i.e. the works of Galileo. Descartes wrote: "I see nothing in his books which I could envy or adopt for myself." This can probably be accounted for by the difference in method: Galileo described things, and Descartes looked for their causes.

According to Descartes, the universe had evolved out of 'fine matter' (it was again termed 'ether') which occupied all of space and was in constant vortex motion. Similar to Aristotle, Descartes did not believe in a vacuum. Particles of fire, air, and earth different in size and form developed from the particles of that fine matter as a result of interactions. The first particles constituted the matter of the Sun and other stars, the second made up that of heavens, the third formed the matter of the Earth and planets.

Having learned about the trial of Galileo for his demonstration of the Earth's motion, Descartes wrote in one of his letters to Mersenne*: "...if the Earth's motion is a lie, then all foundations of my philosophy are false since

* A man who served a kind of 'journal' for scientists to exchange information.

they clearly lead to the same conclusion." To avoid a conflict with the Church, Descartes described the Earth in his system as a motionless planet carried around the Sun by a vortex. Yet the very idea of the possibility that other worlds existed resulted in the prohibition of his works.

Descartes formulated three principal laws—'rules'—of nature. Before that he was the first to determine uniform motion as the rectilinear displacement (Galileo believed it to be circular) of bodies with no force applied. The first and third 'rules' taken together express the principle of inertia of motion: any body tends to keep uniform motion in a straight line. The second 'rule' reads that the general momentum is conserved when motion is transferred. Thus Descartes originated a *measure of motion*, which was a milestone in science. However, the committed two errors in the definition of 'momentum' as the product of the 'quantity of a body' by the velocity of its motion: (1) he assumed in most cases that the 'quantity of a body' was weight instead of mass; (2) he did not take into consideration the direction of velocity, i.e. the vector nature of momentum. The first error is forgiveable since nobody was aware of the notion of mass at that time. But the second error is astonishing for the great geometrician.

These errors were immediately evident in collision theory which Descartes speculatively invented to extend the three 'rules of nature' since interaction in mechanics is reduced to either pressure, or thrust, or collision. He forgot what he had said four years earlier when he had compared the forces of pressure and collision: "I cannot tell how much weight is required to equal a hammer strike: this is a practical issue where *reasoning is useless if not supported by experiment.*" (Author's italics—*G.A.*) The same happened to his theory. When eight rules of collision were tested experimentally, seven of them proved incorrect. There was one more error besides those mentioned above: Descartes did not take into consideration the difference in the interaction of elastic and inelastic bodies. He believed that in the mutual collisions of any bodies, the arithmetical sum of the scalar values of momenta should be the same before and after the collision. Yet when primitive experiments with billiard balls demonstrated that the assumption was erroneous—the sum of momenta decreased and increased depending on the sign and angles between the velocity vectors—Descartes declared that this resulted from the inaccuracy of the measurements. Indeed, how could he admit that the major natural-philosophical principle of his theory—that of the indestructibility of motion—had proved wrong! The philosopher in him defeated the geometrician. (But this is better than had it been vice versa.)

Despite the errors mentioned, Descartes' declaration of the principle of conservation of motion and a measure of motion was of great importance for the formation of the notion of energy and the discovery of the principle of its conservation. We cannot fail to note that Descartes, yet unaware of the notion of mass, distinguished between the 'force to be at rest' and the 'force to persist in motion', the first of which can be considered a conjecture about the inertial mass of a body, expressed earlier and independent of Torricelli. He also introduced a highly important notion: 'momentum of force', i.e. the product of the magnitude of force applied to a body by the time of its action ($F\tau$) which is equal to momentum: $F\tau = m\omega$ and presently identified with the latter. Since matter is endowed with initial motion in Descartes' theory, 'forces' are not the cause but an effect of motion. This however occurs when 'forces' are associated with work or energy. The motion and interaction of particles of 'fine matter' and three elements result in the generation of light, heat, and gravitation. Descartes accounted for the gravitation towards the center of the Earth, for example, as follows: particles of fine matter move vortically and away from the center, while heavier particles of earth take their place.

N. A. Umov wrote: "The Cartesian point of view results in a specific concept of energy. When I raise a stone from the surface of Earth, I accumulate work in the system *stone-earth*, the so-called potential energy which develops and can be taken from this system when the stone falls down to Earth. The energy contained in a moving body is kinetic energy. Thus we find two forms of energy in nature: potential and kinetic. From the point of view of the modern Cartesians, only one form of energy exists, that is, kinetic. Potential energy is the kinetic energy of motions concealed from our eye."

Hence, gravity, according to Descartes, similar to any other force, results from the motion of matter and is in no way a property of a body. If we identify 'fine matter' with space, we could presently say that gravitation in Descartes' theory becomes a property of space. Gilbert and Kepler associated gravitation with the bodies themselves. Galileo (and later Newton) also did not identify it with the properties of space and time. The mechanistic view of Descartes also opposed atomism according to which atoms create fields of forces and their latent motion accounts for all physical processes. It should be noted that Descartes used the term 'force' in the meaning of action, i.e. energy or work. He frequently treated the principle of the latter's conservation as a law which calls for no proof. Descartes' 'force' depends on the value of force in its modern meaning (a measure of the interaction of bodies) and on the projection of the traversed distance on the direction of the action of force. Hence, the 'force' engaged to lift a weight is measured by both these values, while the force engaged to support it is measured by only one of them. Descartes wrote: "These forces differ from each other in the same way as a surface differs from a line." Proceeding from this he 'proved' that the 'force' capable of lifting 2 kg of weight to the height of 1 m or 1 kg to the height of 2 m is twice that capable of lifting 1 kg to the height of 1 m, which is in both cases incorrect since this procedure implies not force but work.

Descartes also did not accept the laws of the fall of bodies discovered by Galileo because he was unaware of the notion of acceleration and the relationship of force to acceleration, although the latter was a consequence of his own formulation of the equality of momentum and the quantity of motion: $F\tau = m\omega$, i.e. $F = ma$, where $a = \omega/\tau$ is acceleration. This, however, did not prevent Descartes from declaring that the "stone in no way tends to take on new motion or increase velocity either when it moves very fast or when it moves very slowly". The full importance of this conjecture was realized only by N. A. Umov in 1896. He predicted that the mass of a body should increase at velocities approaching the velocity of light. Yet J. J. Thomson proved this independently already in 1881 when he treated the motion of a charged ball theoretically. The idea was further developed by H. Lorentz and then by A. Einstein to result in the well-known ratio of energy E to mass m, i.e. $E = mc^2$, where c is the velocity of light.

Thus human reason broke through the web of errors and gradually developed correct ideas and notions associated with energy. Descartes originated a number of general ideas, although he failed to treat minor details. Yet his works were one more step forward in the direction of general progress. Descartes' theory spread quickly over Europe, eliminating the last remnants of Scholasticism. Having fulfilled its beneficial mission, the doctrine, however, was finally defeated and discredited by a theory free of general ideas but rich in thoroughly examined details. This was Newton's theory.

"No Forces Are Lost for Any Type of Motion of Bodies. . . ."

The president of the Paris Academy of Sciences Bernard Le Bovier de Fontenelle, who virtually set a record among scientists, living for 100 years (b. 1657, d. 1757), wrote: "Descartes has given us a new method of reasoning much more attractive than all his philosophy, a major part of which is either erroneous or dubious according to the very rules which he himself propounded." And he was absolutely right. Only two erroneous theses of Descartes' theory—the impossibility to create a vacuum and the definition of momentum as a value having no direction—resulted in so many absurd conclusions that the further progress of science was impossible if they were not refuted. The first distorted the notion of the forces of gravity and 'lightness' and complicated their measurement, while the second perplexed collision theory and the explanation of a number of other phenomena as well as impeded the formation of the notions of force, momentum, and energy.

Galileo already knew from the experience of Florentine plumbers that the "force of abhorrence of a vacuum" cannot exceed the weight of a water column 10 m high. He intended to measure it with the help of a weight which separates a piston from the bottom of a cylinder to which it should be firmly fitted. Soon Evangelista Torricelli (b. 1608, d. 1647) investigated the action of gravity on liquid and established that the rate of the flowout of the liquid is equal to the velocity of its fall from height h of the liquid's level in the vessel ($\omega = \sqrt{2gh}$). Torricelli was also the first to establish that the maximum capacity of pumps to lift water is equal to atmospheric pressure (10 m of water column) under the action of which water is sucked. Finally, in 1643 Torricelli and Viviani carried out the experiment designed by their teacher, at the deathbed of whom they both had stood a year earlier: this was the famous experiment with a piston, in which water was replaced by mercury. A vacuum was formed in a cylinder at the height of the mercury column approximately 14 times less than that of the water column; this column fluctuated depending on the state of the atmosphere. Thus the existence of a vacuum and atmospheric pressure was demonstrated simultaneously! The discovery of a vacuum was long expected and surprised very few. But atmospheric pressure seemed unbelievable: How can a person fail to feel a force of a thousand kilograms upon his shoulders?!

Yet the Cartesians persisted in repeating that Torricellian vacuum was a "space with rarefied air". The Frenchman Blaise Pascal (b. 1623, d. 1662) continued the experiments. His short life was really illustrious: he was engaged with physics for only three or four years but managed to perpetuate his name in the history of this science; he took the monastic vows and in 1657 published *Les Provinciales* (the "Letters of a Provincial"), a pamphlet against Jesuits, which survived 60 printings and gave rise to the new French literature. Having established by his own experiments the correctness of the results obtained by Torricelli, Pascal carried out Descartes' idea to measure atmospheric pressure at different altitudes. The mercury column decreased with an increase in altitude.... This seemed to have left no room for further debates, but Descartes declared: "A vacuum exists only in the head of Pascal!"

The term 'work' was frequently used by Pascal as well as by scientists before him. Pascal applied this term and the principle of virtual displacements to liquids. He w ote: "Since the distance traversed increases proportionally to the force in all simple mechanisms such as the lever, block, and screw, it is absolutely unimportant in hydrostatics whether 100 pounds of water cover a distance of 1 inch or 1 pound of water covers 100 inches." With the help of this principle he formulated the principle of the equal pressure of liquids against the walls of their vessels, the principle of communicating vessels, the principle of the hydraulic press, and other principles of hydrostatics. In this field he was by far more efficient than Benedetti, Stevin, and Galileo.

The enormous value of atmospheric pressure was in such obvious conflict with 'common sense' that the problem aroused the interest even of the members of the Bavarian Reichstag and the Elector himself. The above-mentioned burgomaster O. Guericke demonstrated for them a sensational experiment on the 8th of May, 1654. He pumped the air out of two copper hemispheres closely attached to each other and having a diameter of about 0.3 m, after which two 8-horse teams could hardly separate the portions with the noise of an explosion.

Finally, the famous chemist Robert Boyle (b. 1627, d. 1691) arranged a multitude of experiments, processed data obtained by other researchers, and established that the specific volume of air is inversely proportional to its pressure at constant temperature ($p_1v_1 = p_2v_2$).

This clarified one more type of force (elastic or 'pneumatic') and broadened the concept of gravity. The 'weightless' air proved to have weight just like a stone.

Christiaan Huygens (b. 1629, d. 1695) contributed greatly to the formation of notions such as 'force', 'momentum', and 'energy' by having corrected Descartes' second mistake in collision theory.

In 1668 the Royal Society of London announced a competition to solve the problem of collision. Correct answers were supplied by the mathematician J. Wallis (for a central collision of two equally inelastic balls), the architect Ch. Wren, and ... the lawyer C. Huygens (for elastic balls). Huygens solved this problem already in 1652 but refrained from publishing the results because he did not wish to vex his father who considered Descartes infallible. The 23-year-old lawyer demonstrated that, according to Descartes' theory, "when two bodies collide, their momentum can increase or decrease, but its value remains unchanged if we deduct from it the momentum in the inverse direction". In other words, only the vector quantity of momentum is conserved. Thus Descartes' philosophical principle of the 'conservation of motion' was finally quantitatively expressed (however, it was not yet complete since the notion of mass remained vague).

Huygens developed numerous conjectures about the existence of the principle of conservation of 'force' (energy) into more concrete, rational, and extensive notions. Investigating the principles of the pendulum oscillation, he proceeded from the following rule: "In the motion of bodies induced by gravity, the common center of gravity of these bodies cannot rise above the initial position." Galileo, Torricelli, Stevin, and others expressed ideas close to those mentioned above. Yet Huygens wrote: "If designers of new machines who are fruitlessly trying to construct a perpetual motion machine applied my hypothesis to their efforts, they would easily realize their error and understand that such an engine can never be constructed by mechanical means." Two years before his death Huygens expanded the formulation of the 'hypothesis': "Forces vanish and disappear for any type of motion of bodies with the exception of a certain action which requires the application of the same force which has been expended; we term force a potency required to lift a weight; double force (P) can lift the weight to a double height (h), i.e. $P_1h_1 = P_2h_2$." Since $P = mgh$ is the potential energy of gravity, this is almost a formulation of the principle of conservation of energy in mechanics, but it lacks a clear expression of kinetic energy. Yet the latter can be derived therefrom if we recall that, according to Galileo's laws $\omega = g\tau$ and $h = g\tau^2/2$, height $h = (g/2)(\omega/\tau)^2 = \omega^2/2g$. If we substitute this value into the expression of Huygens' 'hypothesis', we shall derive $P_1\omega_1^2/g \times 2 = P_2\omega_2^2/g \times 2$, where $P/g = m$ is mass. Then $m_1\omega_1^2/2 = m_2\omega_2^2/2$ is the principle of conservation of 'animate forces' (this term dates from Gottfried Leibniz, or Leibnitz), i.e. kinetic energy. This very principle was formulated by Huygens for elastic collision (although his was not yet a final formulation) to extend the principle of conservation of momentum: "In the mutual collision of two bodies, the sum of the products of their quantities (the notion of mass is absent again—*G.A.*) by the squares of their velocities remains constant before and after the collision." The quantity $m\omega^2$ was mentioned by him as well as the quantity $m\omega^2$ was mentioned by him as well as the quantity $m\omega^2/2$, which was determined by Coriolis 177 years later.

It is interesting that Wren arrived at the same conclusion when he treated elastic collision, and Wallis demonstrated that $m\omega^2$ is not conserved in the inelastic collision (since the deformation of balls results frequently in the transfer of 'animate force' to the internal elements of material).

Thus the second measure of motion emerged to give rise to the argument about the correctness of both measures: the 'argument about two measures of motion'.

Huygens' treatise "On Centrifugal Force" (1703) contributed greatly to the generalization of the principles of mechanics already established and the formation of the notions of force and mass. This was the first investigation into the motion performed under the action of force different from gravity, and one more step, after Galileo, towards the discovery of the ratio of force to acceleration. The tension of a thread proved proportional to the acceleration of the weight ripped off the thread. Huygens developed a clearer idea of centripetal and centrifugal forces than that of Benedetti and Descartes. He related them to the same category as gravity, thus making the notion of force even more general. This enabled him to apply Galileo's conclusions for free-falling bodies to bodies performing circular motion and derive a formula for the centripetal force $F = m\omega^2/R$, where R is the length of the thread or the radius of the rotation of the body. Huygens also demonstrated that the centripetal force turns Aristotelian uniform circular motion from a 'natural', i.e. inertial, into a 'forced' motion, while the centrifugal force stretches the thread and thus turns itself into an inertial force.

Animate and Inanimate, Active and Passive Forces

The German scientist Gottfried Wilhelm Leibniz (b. 1646, d. 1716) contributed a great deal to the correction of Descartes' second error and the development of the right interpretation of the principle of indestructibility of motion. This admirer of Descartes and follower of Huygens could not stand aloof from the argument about two measures of motion. In 1686 Leibniz published a treatise "A Brief Demonstration of the Notable Error of Descartes and Others Concerning the Law of Nature According to Which God Always Preserves One and the Same Momentum and Which Is, By the Way, Wrongly Applied to the Practice of Mechanics". In this and in works which followed, he developed Huygens' ideas of the vector nature of momentum and the principle of conservation of 'animate forces' (he introduced the term in 1692) and extended this principle to a universal law of nature.

Leibniz wrote: "*It is wrong ... to reduce all the multiformity of nature to pure mechanics.* I see a corroboration of this in the principal law of nature which implies not the conservation of one and the same momentum but requires the conservation of one and the same *amount of active force...* one and the same *quantity of motive activity* which is far from the Cartesian idea of momentum." (Author's italics—*G.A.*) How close had human reasoning come to the discovery of the principle of conservation of energy 160 years before it was finally established! The 'active force' and 'motive activity' are in fact energy. Only the absence of knowledge and data on the variety of the forms of motion in nature, without which this principle is absurd, impeded its earlier formulation. Leibniz's rejection of the Cartesian universal mechanism should be mentioned specially here. His statement on the 'multiformity of nature', not being limited by pure mechanical phenomena, can be considered a conjecture of the variety and interconvertibility of the forms of motion. This confirms his interpretation of the seeming loss of the 'animate force' in the inelastic collision of 'soft bodies' determined already by Wallis. Leibniz wrote: "That which is absorbed by the smallest atoms is not absolutely lost for the universe, although it is lost for the total force of colliding bodies." His tireless efforts to establish the principle of constancy of 'animate forces' in all phenomena of which he was aware were also a sign of the above-mentioned conjecture.

Leibniz's idea of the notion of force as a certain active element approaches that of the Cartesians. However, he measured this element only by the product $m\omega^2$, which is a measure of forces generating motion (hence the 'animate force'). He termed the Cartesian measure of motion $m\omega = Ph/g\tau$ an 'inanimate force' because he considered it a measure of forces which generate no motion but have only a potential for it: the force of a compressed spring, the gravity of a body at rest, and so forth. Similar to Huygens, he derived the expression $m\omega^2$ and the constancy of this quantity from the fall of bodies and collision of balls, but omitted the figure 2 from the denominator.

Leibniz did not accept the principle of conservation of the Cartesian scalar measure of motion which increases in some cases. Yet this idea did not exclude the possibility of constructing a perpetual motion machine which Leibniz himself considered an absurdity. He formulated the 'principle of conservation of direction' or 'forward motion'. Leibniz wrote: "Besides the above-mentioned law of nature which reads that the sum of forces remains constant, there is another principle no less general and no less rational: the quantity of direction remains constant in bodies connected with each other and in all of nature." The sum of 'directions' is the vector sum of momenta, and the principle is a corrected version of the principle of conservation of momentum.

Thus Leibniz summed up that stage of the argument about two measures of motion. The followers of Descartes and supporters of Leibniz continued the argument for several more decades. The heated exchange brought about a lot of interesting ideas, among which the views of Johann Bernoulli (b. 1667, d. 1748), a prominent scientist of the time, should be given special mention. It is notable that he used the term 'energy' to denote the product of force by the projection of the distance traversed by the force (in a letter to Pierre Varignon dated January 24, 1717). A similar quantity had been used by Descartes who termed it 'force' to express work. J. Bernoulli wrote in 1735: "If the quantity of animate forces—the only source of the continuity of motion in nature—could not be conserved and, consequently, there were no equality of the acting cause and its result, all nature would fall into a disorderly state." Shortly thereafter, in 1738, his brother Daniel derived the famous Bernoulli's theorem which is a mathematical statement of the principle of conservation of energy applied to the steady motion of an incompressible fluid acted on by external forces.

Soon, however, the prominent French scientist and philosopher J. D'Alembert (b. 1717, d. 1783) took part in the argument about two measures of motion and did his best to turn it into an "argument about words unworthy of philosophers' attention". He considered both measures of motion (mechanical!) formally equivalent if the 'animate force' is related to the distance traversed, and the 'inanimate force' is related to time. This, however, did not eliminate the qualitative differences between them, which were fully realized only after the discovery of other forms of motion and their interconvertibility.

Many years later F. Engels treated the argument of the advocates of two measures of motion and arrived at the following conclusion: "...$m\omega$ is mechanical motion measured by mechanical motion; $m\omega^2/2$ is mechanical motion measured by its capacity to become converted into a definite quantity of another form of motion."

Thus motion is characterized both by the conservation of the quantity of motion—momentum—and by the conservation of energy. It will be shown below that the relation of these quantities to each other is determined by the relation of the properties of space to the properties of time. In the search for the origins of forces, Leibniz suggested the idea of monads—immaterial, indivisible, self-acting substances which are the basis of all things. God was, in his theory, a monad of monads. V. I. Lenin wrote that Leibniz "through theology arrived at the principle of the inseparable (and universal, absolute) connection of matter and motion.... Monads=souls of a certain kind.... And matter is something in the nature of another being of the soul, or a jelly linking them by a worldly, fleshly connection".

Leibniz developed his theory of monads to divide forces into active and passive. Active force is the soul of matter, an inherent capacity to move; passive force is the force of resistance, or inertia. Nature endows all monads with both types of forces, but active force starts to act only after the obstacle which impedes its action has been removed. Thus, for example, the bowstring launches the arrow after having been released by the hand. The nature of forces is immaterial and incognizable in Leibniz's theory.

As we see, Descartes excluded force as the initial cause of motion from the material system of the world, for him God was the prime mover, and forces appeared as a result of the motion of matter. Leibniz, on the contrary, saw the true essence of matter in force.

Innate and Impressed Forces

In February 1650 the great Descartes was living the last days of his short life in cold Stockholm. At that very time an ailing boy was going to a country school somewhere in misty Albion. Two decades later this boy attacked the Cartesian theory and razed the doctrine to the ground. His first move was to discard the basis of the theory—the method. "I feign no hypothesis!" he protested proudly against the groundless speculations and fantastic constructions of the orthodox Cartesians. He made induction the basis of his method, but did not absolutely discard deductive reasoning, although he gave priority to the former. Naturally, he could not help 'feigning' hypotheses as there is no science without them, but his hypotheses were firmly supported by experiments and expressed mathematically. The boy continued the cause of Galileo, which had been interrupted by the Cartesians. He was really the founder of modern physics.... But with him also started 'Newtonism'—a tendency to 'ban hypotheses in physics'; this trend originated a reactionary school of 'pure description' of phenomena unconcerned with their nature—a school close to the idealist philosophers Berkeley and Mach who considered the nature of things incognizable.

Proceeding from the principle which he had proclaimed, the boy would accept neither the conservation of motion (or momentum) like Descartes nor the conservation of 'animate forces' like Leibniz. He was pious and his theory, "inevitably leading to the recognition of a superior being which had created and freely organized everything" (Voltaire), got along with religion much easier than the Cartesian theory in which God was the creator of matter and motion.

This boy was Isaac Newton (b. 1643, d. 1727). Newton lived a long life during which he tried an impressive number of various occupations such as mathematics, optics, mechanics, astronomy, chemistry, thermal engineering, and even history and theology. Yet he said at the end of his life: "I don't know how I appear to the world, but I myself believe that I was only a boy playing on the seashore and my entertainment was to find from time to time a smoother stone or a more beautiful shell than usual, while the great ocean of truth lay before me absolutely undiscovered." He was a contemporary of Huygens, Leibniz, Boyle, Hooke, and Peter I, the great reformer of Russia. Alexander Menshikov, one of the closest associates of Peter I, was appointed a fellow of the Royal Society of which Newton was the President at the time. And two years before Newton's death Menshikov and Catherine I inaugurated the Petersburg Academy of Sciences established by Peter I. Lomonosov, a great Russian scientist, was 16-years-old when Newton died. Three years later Lomonosov left his native village of Kholmogori to start his ascent along the rocky and precipitous paths of Russian science.

Newton was born into a family of less than adequate wealth. Having graduated from school in the city of Grantham, he entered Trinity College of the University of Cambridge. Want of money made him turn for employment as a valet to the fellows of the college. This unpleasant necessity depressed Newton, but he found comfort in his studies in which he made rapid progress. He studied works by Descartes, Wallis, Kepler, Galileo, Hooke, and Huygens and succeeded in getting all scientific degrees and titles available at that college in a mere seven years. He was 26-years-old when he became the head of the Department of Mathematics. By that time a great amount of scientific data had been accumulated, the number of scientists had rapidly increased, and many of them were approaching—sometimes groping their way and sometimes moving deliberately—the establishment of relevant dependences. The prestige of scientists was rising and the most successful of them started to receive honors and money prizes. This induced the struggle for priority.

A plague epidemic made Newton seek for shelter in his native village of Woolsthorpe between 1664 and 1667. During these and the years which followed he was preparing his great discoveries: the decomposition of the white color into seven components and a description of colors; 'theories of fluxions', i.e. differential calculus (Leibniz developed the same theory approximately at the same time and independently of Newton); the law of universal gravitation. The development of a comprehensive system of mechanics was also one of his major achievements of that period.

Colors were believed then to result from the mixture of white and black colors. However, a Prague professor of medicine, J. Marci, observed the decomposition of the white color with the help of a prism in 1648, but failed to elucidate the phenomenon correctly. Newton defied 'common sense' by having established experimentally that white results from a mixture of red, orange, yellow, green, blue, dark blue, and violet, all of which have different refractive indexes. On this basis, having arrived at the erroneous conclusion about the impossibility of eliminating chromatic aberration (the image of a point source of white light is blurred and appears colored) in lenses, Newton constructed a new type of telescope with concave mirrors thoroughly polished. The telescope was sent to the Royal Society where it was submitted to a special commission and tested by the ... King. Newton became a fellow of the Royal Society on the 11th of January, 1672, and already in February his treatise on the nature of light was published in the journal of the Society. The treatise aroused a hurricane of protests (nobody could believe in a discovery which so blatantly contradicted traditional views) in which even Robert Hooke (who had authorized the publication) took part. This response to Newton's discovery insulted him such that he resigned his fellowship of the Royal Society and refused to answer articles and letters. A new treatise published in 1675 brought about similar polemics, and Newton swore not to publish anything while Hooke was alive. "...I am convinced that one should either report nothing new or else he must give all his energy to defend his discovery," wrote Newton.

Soon, however, a new scandal broke out because of the priority in the discovery of the law of universal gravitation. The problem was treated simultaneously by Kepler, Roberval, and Borelli. Yet it was Huygens who derived in 1673 a formula for centripetal force, thus making it possible to establish quantitative dependences. Three fellows of the Royal Society, Hooke, Halley, and the above-mentioned Wren, directed their efforts at this objective. Robert Hooke was known for his capacity to grasp at the relevant problems of the time and determine their nature. In 1674 he published a treatise "An Experiment to Demonstrate the Motion of Earth by Observations" in which he gave an almost complete theory of gravitation. Several years later, on the basis of Kepler's third law, Edmund Halley arrived at the conclusion that the gravitation of the Sun should also decrease inversely proportional to the square of the distance between planets and the Sun, and made an attempt to determine their orbits. Having failed in that and receiving no help from Hooke and Wren, he turned to Newton who surprised him not only by a ready solution but also by an impressive number of important findings. Halley suggested an immediate publication of the discoveries, but Newton wished no new conflicts and scandals and refrained from publication till 1686. When he did submit his findings to the Royal Society, Hooke hurried to declare that Newton took advantage of the results obtained by him. Newton wrote Halley a sharp letter in reply where he pointed out that Hooke himself borrowed his evidence from Borelli and probably from Newton when the latter informed Huygens in 1673 of the principle of inverse squares in a letter addressed to the Royal Society, the Secretary of which was Hooke. The conflict was somehow settled, and three volumes of Newton's works were published in 1687 under the title *Philoso-*

phiae Naturalis Principia Mathematica ("Mathematical Principles of Natural Philosophy"). The work mentioned the names of Hooke, Wren, and Halley. The first two volumes treated classical mechanics, the third employed the laws of mechanics to describe the system of the world. This was celestial mechanics which could not fail to infringe upon the interests of the official Christian ideology. Newton hesitated to publish the third volume for a long time. He wrote on May 22, 1686: "I intend now to exclude the third volume; philosophy is such an impudent and litigious lady that any business with it means a lawsuit."

Newton also contributed to mechanics by systematizing results supplied by his predecessors and laws which had earlier been applied to specific cases. It is of special significance for us to mention that *he was the first to separate clearly the quantity of mass m from the quantity of weight*: $P = mg$ (where g is the acceleration of free fall). Weight at last became equivalent to the notion of force. Yet Newton's definition of mass was tautological and left room for heated discussions which were not to stop for a century. The matter was that Newton believed the world to consist of "solid, ponderable, impenetrable, and mobile particles" and its qualitative variety was the result of differences in the motion of particles. This is a clearly mechanistic idea. Hence, mass in Newton's theory is a measure of the amount of matter proportional to its density and volume: $m = \rho V$. Thus mass was determined in terms of density ρ, although density is ... mass per unit volume: $\rho = m/V$.

Mass is now defined as a measure of the inertness of a body, characterizing the rate of change of its velocity under the action of the given force, which is closer to the definition of the 'quantity of body' by Torricelli and Descartes.

Newton defined momentum as the product of the mass of a body by its velocity and considered it to be a vector quantity. Like Descartes, he reduced all forms of motion to mechanical and was far from treating the conversion of mechanical motion into other forms, a process already discussed by Leibniz. Yet, in contrast to Descartes, he believed that "momentum is not always the same in the world.... Motion may set in and cease. But owing to the viscosity of fluids, friction of their particles, and low elasticity in solid bodies, motion ceases more than it sets in and is always in a state of decrease.... Thus we see that the variety of motions which we observe in the world constantly decreases and there is a need to conserve and replenish it by means of active elements" (Newton's 'active elements' also included gravitation). The last statement contains a hint at the principle of degradation of energy.

Newton introduced the notion of mass and was thus privileged to employ force without giving a thought to its physical meaning. (D'Alembert in 1743 and Heinrich Hertz in 1891 made an attempt to construct mechanics without the notion of force, but their theories were not widely recognized because of their complexity.) Yet Newton also wished to describe forces qualitatively. He classified them into 'impressed' and 'innate'. The former are "actions performed upon bodies to change their state of rest or of uniform motion in a straight line". In other words, 'impressed force' is a cause of the irregularity or curvilinearity of motion. It is not expended (like the 'force' of Descartes or Leibniz) and can act on an unlimited number of bodies during unlimited time, but it does not remain in the body after the action ceases, and the body conserves the acquired state only owing to inertia. Thus, *according to Newton, the active element is outside matter, separate from it.* This idea enabled him to discuss how motion is set in and ceases. "Innate force is a power of resistivity by which each individual body, if it is left to its own devices, persists in its present state of rest or of uniform motion in a straight line." This is in fact the force of inertia proportional to mass.

Newton established that the 'impressed' force of a body is equal to the change of momentum of the body per unit time: $F = \Delta mV/\tau = ma$, i.e. the product of mass by acceleration. Yet Newton did not term it 'acceleration' but treated it as the 'rate of velocity change'. According to Newton, the action of force may be direct, contact-type, or indirect—generated by a remote force center. He termed the force acting from a distance a central or "centripetal force which makes bodies be attracted to, race for, or approach in any way a certain point as if it were a center"; he put, for example, gravity and magnetic force into this category. Central forces have three 'values'. The absolute value is determined by the 'active cause' generated by the force center (gravitational mass, magnetic mass, etc.), the motive value expresses the change of momentum induced by the given force per unit time, and the accelerating value is proportional to the acceleration imparted to a body under the action of force, whereas force is related to mass as follows: $F/m = \Delta\omega/\tau$.

In modern terms these three 'values' are characteristics of any force field: the absolute value is the charge (gravitational, magnetic, etc.), the motive value is the pondermotive ('mechanical') force, and the accelerating value is the intensity of the force field. We shall demonstrate them below by concrete examples.

Having applied the rate of change of momentum to characterize motion, Newton constructed his dynamics on the basis of this quantity of motion. Yet Leibniz's 'animate force' is an energy characteristic of motion. Thus the functions of these notions are in no way identical but differ decisively from each other.

The *Principia* ("Principles") formulated three laws of mechanics which are presently common knowledge: the law of inertia, the law expressing the proportionality of force to acceleration ($F = ma$), and the law of the equality of action and reaction. The law of gravitation was formulated in the third volume of the *Principia* on the basis of experimental data and the general rules of research into nature. The law reads: the force F of the attraction between two bodies of masses m_1 and m_2 separated by a distance x is directly proportional to the product of their masses and inversely proportional to the square of the distance between them, i.e. $F = Gm_1m_2/x^2$, where G is the gravitational constant.

Newton wrote: "By the term 'gravitation', I mean a general attraction between bodies; it is irrelevant whether this attraction is generated by the bodies themselves, or whether the bodies collide because they are launched by spirits, or it is induced by ether, air, or any corporal or incorporal medium which drives bodies floating therein into collision."

The developed notions, laws, and relationships helped Newton to investigate various phenomena and obtain a great number of extremely important results. Newton ignored, however, the interconversion of different forms of motion and neglected the notions of work and energy. Only occasional 'instructions' and examples in his works contain the product of force by velocity (power = work per unit time), the theorem on animate forces applied to specific problems, and so forth. Thus the 'instruction to the third law' reads: "If the action of the motive force is proportional to the product of this force by velocity, and the reaction of resistances of every separate part is proportional to the product of its velocity by resistance occurring due to friction, cohesion, weight, and acceleration, then the action and reaction will be constantly equal in any mechanism." This statement inspired the British physicists W. Thomson, Tait, and Maxwell to declare that Newton's theory "covers almost all theories of energy". Yet the above-mentioned citation is the only place in Newton's works which may be interpreted from an 'energy' point of view with a very strained interpretation and by means of the level of knowledge accumulated on by the middle of the 19th century, which made the statement by the British scholars seem rather premature.

The last 40 (!) years of Newton's life were not marked by any significant scientific achievements. His social position became very high. He was a Member of Parliament between 1688 and 1694. Newton was appointed warden of the mint in 1695 while retaining his professorship at Cambridge, with a promotion to master of the mint in 1699 with a salary of £12 to 15 thousand per year. He moved to London where he was immediately elected President of the Royal Society. In 1705 Newton was knighted by Queen Anne.

In his last years Newton wrote, like Boyle, theological compositions—a treatise about the prophet Daniel and an interpretation of the Apocalypse. He suffered from gout, rheumatism, and gallstones, but presided over a session of the Royal Society a month before his death. King George I issued a special order to bury Newton in the Westminster Abbey. He was buried with high honors and the funeral was attended by two dukes, three peers, three earls, and all the fellows of the Royal Society. The ceremony bore no resemblance to the funeral of Galileo. Less than 100 years had passed but the change in attitude was so evident and so dramatic....

After Newton's departure, works of Euler (1736), D'Alembert (1743), and Lagrange (1788) brought mechanical problems to the level of mathematical problems, the solutions of which were much easier owing to the development of differential calculus.

The mechanics refused to consider the 'vague' natural-philosophical idea of conservation of motion (or force) just when their own science was on fertile ground to turn this idea into an exact law of nature available for mathematical processing and experimental demonstration. By the end of the eighteenth century, science had already been operating all notions required to formulate the principle of conservation of energy in mechanics. The expression $K + P = \text{const}$ was derived, where K is the 'animate force' and P is the potential function, but this expression had no other meaning at that time than a formal mathematical one. Even the physical meaning of the 'equation of animate forces' $\Delta m\omega^2/2 = Fl$ remained vague because of the uncertainty of its right-hand side (Fl), i.e. the notion of work which had been applied intuitively for a long time.

Thus "philosophy takes vengeance on natural science for the latter to leave it" (F. Engels).

The Advent of the 'Motive Power of Fire'

In the Middle Ages the energy of numerous slaves, which served not as labor hands but as a source of motive power, was being increasingly replaced by the energy of animals, water, and wind. In the tenth century, men learned to shoe draught animals, and in the eleventh century, the shoulder collar succeeded the ancient neck collar which increased tractive force by four times. Placing several animals in one team was a new and the latest leap in the evolution of muscular force. The 11th century in Europe was marked by the extensive spreading of the long-ago-invented water- and windwheels. These new sources of power stimulated rapid progress in metallurgy and mining. A horse replaced ten slaves, and a good water- and windwheel substituted for a hundred.

Yet the final transition to a fundamentally new power engineering—heat and power engineering once discovered by Hero of Alexandria—had to wait until the 17th and 18th centuries. The new technology implied a distinct conversion of the thermal form of motion (energy) into mechanical form (energy), and the latent conversion of the chemical form (energy) into thermal form. This transition could have waited for much longer if it had not been effectuated by the rapid advance of production technology.

The industrial boom started with the appearance of cotton in colonial markets. Compared to flax, cotton was sold for a next-to-nothing price. This signalled great profits but the traditional manufactory was incapable of processing this material. The old 'low-speed' manufactory in which both technologies—spinning and weaving—were used had to disintegrate into two independent industries. Arkwright, a former barber but smart businessman, availed himself of an idea which did not belong to him and in 1769 patented a 'water spinning machine'. This enabled him to satisfy his lust for profit by setting up a mighty chain of factories. He was proclaimed a model businessman, compared to Newton and Napoleon, called the pride of the nation.... Bourgeois sociologists did not hesitate to exploit this example to support their theory of social selection which reads that the strong survive and the weak perish, and thus the continuous perfection of humanity is achieved.

Soon the loom was invented. The need to replace wood by iron became urgent. The lack of wood in England caused a decrease in iron production, which had to be imported from Russia and Sweden. This resulted in the replacement of charcoal by bituminous coal in metallurgy, which made possible a large-scale production of pig iron and wrought iron. The crucible steel manufacturing technology was developed in 1750. The development of the metallurgy industry was gaining momentum. The English steel-king John Wilkinson started with one blast furnace in Bradley in 1754 and was coining his own money which was circulated in his region by the end of the century.

Coal and iron-ore extraction could not fall behind melting, metal working was keeping pace—drilling, screw-cutting machines, and lathes were invented—and the construction of machine-tool factories could not wait any longer.

This entire fleet of mining, metallurgic, and manufacturing machines, which had emerged so rapidly and continued to increase in numbers, required a motive power. The muscular force of animals could not meet these requirements, waterwheels were river-based and thus prevented production from coming closer to deposits of minerals (power transmission by electric lines was yet unknown), and wind power was unreliable. Pumping water from mines, the productivity of which was increasing with the development of deeper beds, presented a power problem of special urgency.

Practical workers only had to turn to scientists for instructions about the ways to find and exploit new sources of highly concentrated power, but "physicists were almost uninterested in it; they were equally indifferent to the steam engine during the whole of the eighteenth century and the first decades of the nineteenth" (F. Engels). Thus practical workers had to grope their way and rely upon intuition and experience.

There was nothing left besides the 'power of fire' converted into mechanical force through the force of steam. The principle is simple: water is boiled in a closed vessel with an outlet tube until a portion of the water converts into steam, under the pressure of which the rest of the water is driven through the tube. If steam from such a 'boiler' is fed through a pipeline to a reservoir at the bottom of a mine, it will also 'press' (pump) water out of it.

In 1615 Salomon de Caus (b. 1576, d. 1626), who administered the fountains at the British Court and taught Princess Elizabeth art, published a treatise "On Motive Forces" consisting of two sections: On Theorems and On Machines. He gave therein one of the first descriptions of a primitive type of fountain water-lifting device in which water was boiled in a large copper sphere to regulate a spray of water from a tube.

More thorough research into steam engineering was conducted by Huygens' assistant D. Papin, a physician by profession who had arranged a number of experiments to obtain a vacuum. In 1680 he invented a steam boiler with a weight-and-lever loaded valve which provided for the control of the maximum pressure of steam in the boiler by adjusting the weight.

A new idea evolved during his experiments to obtain a vacuum under a piston positioned in a cylinder, as had been proposed by Galileo. Huygens suggested that gunpowder be exploded at the bottom of the cylinder which should result in the piston's rapid upward motion producing rarefaction. The piston should have fallen down under atmospheric pressure after the release of a portion of gases. This device simultaneously involved two new mechanisms: the internal combustion engine and the atmospheric steam engine. Gunpowder being a rather unsafe material to deal with, Papin decided in 1690 to replace it by ... water boiled at the bottom of the cylinder and converted into steam, under the pressure of which the piston would go up and 'fall down' after the condensation of steam. To accelerate the condensation, cold water was poured over the cylinder. Papin gave the first correct thermodynamical description of the processes occurring in his engine in a book published in 1698.

If Papin had arranged the working processes in separate units, humanity would have had a steam engine in 1690! Yet the construction of such an engine required an additional 75 years. However, Papin did separate the boiler from the cylinder in 1707. In the new device the steam was fed from above the piston, but the return to the original position was performed under the pressure of water from below the piston. This system, however, was not developed further. The human mind seemed to have been obsessed with the problem of pumping water out of mines, and inventors could not yet associate the reciprocating motion of the piston with the rotary motion of the future mechanical drive. The turbine invented by Hero seventeen centuries earlier presented such a drive, but it was considered a toy unfit for industrial purposes because of its excessively high speed of rotation.

The resulting development of steam engineering progressed along traditional lines. In 1698 the Englishman T. Savery patented a steam-displacing water-raising engine and even advertised it in a special publication "The Miner's Friend". Yet this 'machine' (in which there was not a single moving part) did not find any significant application because of design inefficiency.

A Dartmouth hardware salesman, Th. Newcomen, constructed a water-raising engine of his own design between 1705 and 1712. His engine was very much like that of Papin, but the pump was for the first time separated from the engine and was actuated by a lever (balance beam), one end of which was connected to the engine's piston rod and another to the pump's piston rod. A weight was fixed to the pump's piston rod to accumulate energy. A system of valves controlled the feed of steam and water to the cylinders. Steam was generated in a special boiler. Newcomen's engine found wide application in mines not only in Britain but also in Austria, Belgium, France, Germany, and other countries. The last engine of this type was still in operation in England in ... 1934.

To increase power, the diameter of the cylinder of these engines was brought up to 1.8 meters and the piston stroke to 3 meters, the effect of which was a mere 76.5 horsepower. This was a final limit, and a further increase in power required a new technology. On the other hand, there was an urgent need to devise a rotary drive similar to water- and windwheels but independent of rivers and winds, i.e. a multipurpose engine. The early models of such engines were a combination of an engine-pump unit with a waterwheel which rotated under the action of water supplied by the pump.

Only in 1763 the chargemaster of Kolyvano-Voskresensk works I. I. Polzunov (b. 1728, d. 1766) designed a really universal steam engine of continuous action which was to eliminate completely the dependence on water, replace waterwheels and weirs, and "do whatever work we desire". Since it operated on coal, the engine was independent of location, and its working cycle was made continuous by excluding the idle running with th help of two cylinders operated on a common shaft. The engine, however, remained atmospheric, but since it served to drive air-blowing bellows, twice as many furnaces could be operated. Yet the designer met various difficulties impeding the realization of his project which wore him out both physically and morally. He died of galloping consumption on May 16, 1766. His engine was in operation from the 7th of August to the 10th of November, 1766 and then stopped because of a minor malfunction (a leak from the boiler).

The engine and its designer having been forgotten, a laboratory assistant of the University of Glasgow, James Watt (b. 1736, d. 1819), got all the fame for constructing the first multipurpose engine. While repairing a Newcomen-type engine, he detected a number of defects and improved the design; he constructed a steam jacket around the cylinder, separated the condenser from the cylinder, and replaced the motive power of atmospheric pressure by that of elasticity of steam which was fed from above the piston. However, this was still a water-raising engine.

In 1769 Watt patented his device and entered into an agreement with the businessman M. Boulton to found the company 'Watt & Boulton'. When industry required a multipurpose engine, in 1782 Watt made improvements necessary to meet the new requirements, including: double action (steam was fed in turn from above and from below the piston), slide valve steam distribution, conversion of reciprocating motion into rotary motion, and flywheel. In 1788 he introduced a centrifugal governor of the revolutions per minute. The company manufactured 66 engines in the first decade of its activities and 144 in the second decade.

A prominent scientist and leader of the French revolution of 1848, Dominique Arago, would say later: "Watt, gentlemen, has created from six to eight million tireless and industrious workers *who neither strike nor riot and cost a mere 5 centimes per day.*"

Yet Watt's engines were low-pressure devices whose pressure did not considerably exceed atmospheric pressure. The construction of modernized high-speed high-pressure steam engines began only in 1870.

The further progress of technology was directed at the construction of gas engines. In 1801 the Frenchman Ph. Lebon, the inventor of the thermolamp (gas burning lamp), patented a piston engine operating, like the lamp, on combustible gases produced by the dry distillation of wood, the gases being ignited by electric spark and combusted inside the cylinder.

In 1805 a Swiss, J. Rivas, suggested an engine operating on hydrogen, but this gas is considered even today a 'fuel of the future', the production of which will be facilitated by atomic energy.

In 1816 a Scotch priest, R. Stirling, patented a multipurpose heat engine consisting of a cylinder with two pistons and a regenerative heat exchanger. The engine could operate on different fuels and perform functions of an external combustion engine, refrigerator, and heat pump (heater). The low level of science and technology of the time impeded the development of high-efficient types of 'Stirlings', although the engine is currently believed to have a great future.

In 1824 the founder of thermodynamics S. Carnot (b. 1796, d. 1832) outlined a theoretical operating cycle of the four-stroke internal combustion engine, corresponding to the four strokes of the piston: (1) air suction; (2) air compression (at the end of this cycle fuel is fed and combusted); (3) working stroke (expansion of the gaseous products of combustion); (4) release of gases.

In 1860 a French mechanic, J. Lenoir, started to construct and sell internal combustion engines operating on illuminating gas which was ignited by electric spark but without any preliminary air compression, which limited their efficiency to 3 to 5%, similar to that of steam engines. These engines did not find a significant application.

Only in 1877 the German businessman and inventor N. Otto constructed at last a four-stroke gasoline internal combustion engine with a mixture compression and spark ignition. The efficiency of the new engine was 16 to 20%. However, a manuscript by A. Beau de Rochas was found in 1883 in which he had already described a similar engine as early as 1862, and the Frenchmen secured a revocation of some of Otto's patents.

In 1892-1897 a German engineer, R. Diesel, constructed an air-injection internal combustion engine in which air was compressed sufficiently to ignite fuel injected into the cylinder where the combustion actuated a piston. This was the most economical of all internal combustion engines. The design was improved later by the Russian engineer G. V. Trinkler (1904) who constructed an airless injection Diesel engine.

Thus, beginning with 1877, internal combustion engines were becoming more and more economical and more compact than steam engines. The search for a more efficient design of steam engines returned inventors and engineers to turbines. A hundred years ago, Boulton, Watt's companion, feared that the turbine could force out the steam engine, thus damaging the company. "What damage are we talking about," replied Watt, "if there is no way to make the working parts rotate at the speed of 1000 feet per second without the help of God?" Indeed, the low strength of materials, inadequate precision of the machining of working parts, and other causes impeded the manufacture of turbines up to the end of the nineteenth century.

In 1884 an Englishman, Ch. Parsons, patented a steam multistage reaction turbine. In 1889 a Swedish engineer, G. Laval, secured a British patent for a diverging nozzle which allowed, in contrast to the converging nozzle, to convert any steam pressure differential into kinetic energy. In 1891 a condenser was added to the steam turbine to make it more economical than piston engines while conserving its advantage of high power density. This turbine became a major power plant of electric power stations.

The first steam-gas-turbine plant with combustion at constant pressure was designed and constructed in 1897 by the Russian engineer P. D. Kuzminsky. V. V. Karavodin, another Russian engineer, developed a more economical gas-turbine plant with an intermittent process (combustion at constant volume) in 1906, which he constructed in 1908.

Thus started the spread over the world of energy-converting machinery operating on the 'motive power of fire', the impetuous exhaustion of unrenewable energy sources on the Earth, and the pollution of the environment. But humanity was yet unaware of the dangers brought about by the advent of these new machines and rushed forward triumphantly and proudly.

Forces of 'Imponderable' Matter

Thus the above-discussed achievements of science and experience prepared the final division of 'force' into three different notions, i.e. force, work, and energy, as well as the establishment of the principle of conservation and conversion of energy that only a 'couple of days' seemed to separate humanity from that significant moment. Yet the situation which had developed in physics by the middle of the eighteenth century delayed this process by a hundred long years!

The question of the origin of forces was the stumbling block of the time, which induced a heated discussion and distracted the attention of scientists from many important issues. In Descartes' theory, as we have seen, forces were generated by vortex motions of matter 'actuated' by God. Leibniz introduced monads, that is spiritual substances inherent in matter and causing its motion, as the carriers of forces. Newton separated force from matter and considered it an external cause of the change in a body's state. The situation was aggravated by the fact that the argument was about 'forces' in general without any specification of the physical meaning of their different values, although the notion of 'force' was close to the notion of energy in works by Descartes and Leibniz, and Newtonian 'force' corresponded to the notion of the force proper.

The argument began with a discussion of the origin of gravitational forces. The Cartesians denied the 'elemental' character of gravitation, which they considered God-actuated, and tried to develop a mechanical theory of gravitation on the basis of vortex motion. The orthodox Newtonians, on the contrary, considered gravitation an integral property of matter to argue about which was senseless and even impious. They denied any possibility of developing a theory of gravitation, although acknowledged gravitation not only between planets but also between any material bodies down to atoms.

With time, the futility of Cartesian theories became more and more conspicuous, and the Newtonian doctrine supported by new evidence was rapidly spreading. An 'all-out' campaign was launched against the Cartesianism as it had once been the case against Scholasticism. Yet scientists rushed from one extreme to another. The Newtonians began to exaggerate two major ideas of their teacher: the application of mechanical postulates to all physics and the intensification of formalism and empiricism in scientific research.

Newton wrote in the *Principia*:

"...it is desirable that other natural phenomena also be deduced from the elements of mechanics if we follow this line of reasoning, because there is much evidence which makes me believe all these phenomena to be conditioned by certain forces, caused by reasons yet unknown, which make particles of bodies either attract each other and stick together forming regular figures or repulse and move away from each other. These forces being unknown, all attempts of philosophers to explain natural phenomena have remained futile up to now." Further he made the expressed idea more explicit: since bodies interact by means of attraction, gravitation, magnetism, and electricity, the existence of other forces of attraction is probable because there is much "accord and similarity in nature".

The majority followed Newton, although Leibniz wrote at the same time that "it is wrong to limit all natural phenomena to mechanics" and supported his thesis with persuasive arguments. Newton's theory inevitably led to the conclusion that only 'imponderable matter' can be the carrier of forces since all material bodies and particles have weight, while forces are external causes of the motion of bodies, which do not remain in bodies after the action ceases. All forces act from a distance (remote control) similar to gravitational forces. This was the 'logic of reasoning'!

Scientists believed 'imponderable' carriers of forces (fluids) to locate in the pores of bodies. Certain forces were acting between these very fluids and particles of a usual ponderable substance. These forces were intensively searched for. The effect of this search was that the problem of forces turned into a point of discord among physicists in contrast to what once had been when they cooperated to solve the problem of the system of the world. The rapid progress of technology required knowledge of various forces.

The attention of scholars was concentrated on the research into individual phenomena, the collection of unrelated experimental facts and specific dependences. Bacon's inductive method had developed a fear of reasoning, which Newton's principle "I feign no hypotheses" fortified and made fashionable. The time of 'ant-scholars', who, according to Bacon's classification, were continuously collecting facts (a laudable and valuable endeavor!), came, but these 'ants' were 'on principle' either unwilling or unable to understand and generalize the collected material.

Having rejected Cartesian physics because of its weak points, the Newtonians threw out the baby with the bath: the ideas about the material integrity of the world, the uncreatability and indestructibility of motion, the interrelation between phenomena in nature, and the conversion of some forms of motion (even if mechanical) into others. The effect of this was that "materialism travelled from England to France" where it discovered the second materialist-philosophical school developed from Cartesian philosophy and merged with it (F. Engels).

The science-like philosophy of the subjective idealist G. Berkeley (b. 1685, d. 1753) and agnostic D. Hume (b. 1711, d. 1776) became popular in England. These philosophers followed fashion to consider experience the only source of knowledge, but denied that experience helped to cognize the actually existing world. Berkeley admitted the existence of only a 'cosmic mind' and believed that man directly perceived only his ideas (sensations) but not real things. Only spiritual substances are active in his theory, hence he called upon scientists to "learn to understand the language of the Maker instead of attempting to explain everything by mere corporeal causalities". On these grounds he rejected Newton's theory of gravitation as a theory of the natural cause of motion of material bodies. Hume did not believe in God but considered the question as to whether objective world really existed or not to be unanswerable because we perceived it through a stream of impressions, the causes of which were unknown and incomprehensible.

The philosophical school of C. Wolff (b. 1679, d. 1754), an idealist, enlightener, systematizer, and popularizer of

Leibniz's philosophy, was dominant then in Germany. M. Lomonosov was Wolff's disciple. C. Wolff diluted the dialectical elements of Leibniz's theory to develop a metaphysical theology in which universal relationship and harmony were explained by God-established objectives. According to this philosophy, cats were created to eat mice, mice were to be eaten by cats, and all nature was created to prove the wisdom of the Maker. Wolff was one of the active advocates and popularizers of the theory of 'imponderable' carriers of force.

The great enlighteners Voltaire and Rousseau, the materialists Diderot, D'Holbach, and Lamettrie worked in France at that time and their influence was beneficial to the development of natural sciences. Diderot wrote, for example, about forces:

"Some philosophers believe that a body is inert and impotent by nature; this is a dire error contradicting any rational physics and any rational chemistry: *a body is full of activity and potency both by its nature and by the nature of its major properties*, *whether we consider it on the level of molecules or as a mass....*"

There were a lot of natural scientists who took an intermediate position between the Cartesians and Newtonians. To them belonged the great Russian scientist Lomonosov and his colleague at the Petersburg Academy, Euler. Lomonosov (b. 1711, d. 1765) believed, similar to Descartes, matter and motion (still only mechanical) to be the essence of things. But motion cannot spontaneously occur in a body "if the body is not forced into motion by another body" as in Newton's theory. Yet Lomonosov thought that bodies can interact only after having received momentum, i.e. motion; "pure attraction can induce neither action nor reaction in bodies". His views part here with those of the Newtonians and approach those of Descartes and Huygens. He flatly denied imponderable matter and any possibility of remote control.

Euler (b. 1707, d. 1783) began his *Mechanica* ("Mechanics"), published in 1736, in Newton's style. "Force," he wrote, "is an effort which brings a body from the state of rest to the state of motion or alters its motion." The interpretation of force as an effort seems more precise than Newton's definition. Euler defined the 'force of inertia' as a "measure of inertia dependent on the nature of bodies and the cause of the conservation of their state". This resembles Newton's 'innate force'. He was also cautious in his definition of the origin of forces and reserved judgement on "whether forces of these type stem from the bodies themselves or exist in nature independently". Yet his further reasoning was rather Cartesian: "Forces of this type (gravitational, electric, and magnetic—*G.A.*) may stem both from elastic bodies and vortices." In his later works he was against the imponderable carriers and remote control of forces. He considered the inertia and impenetrability of bodies to be an origin of forces. "Force is an external cause," wrote Euler in 1765, "because bodies cannot alter their state independently." And "this very property of some bodies to persist in their state means that they must contain forces to alter the state of other bodies", the cause of which "might be not only inertia but a combination of the latter with impenetrability", i.e. the incapability of bodies to penetrate each other. This "forms an ample source of forces capable of continuously altering the state of bodies".

The German philosopher and scientist, the founder of German classical idealism I. Kant (b. 1724, d. 1804) contributed much to the campaign against the orthodox Newtonians. In 1755 he introduced a hypothesis of the evolution of the Solar system from a nebula, the development of which fully corresponded to Newton's laws. The hypothesis disregarded the 'Maker' and restored the idea of development.

The most popular 'imponderable' matter was thermogen. The term is believed to have been coined by Lavoisier, although the material theory of heat was supported by Galileo, Descartes, and others and spread by Wolff, Wilke, and especially by Black. The heating of bodies was related to thermogen. Forces of repulsion occurred between the particles of thermogen, and forces of attraction acted between the particles of thermogen and those of bodies. Phlogiston was invented to perform the function of 'combustible matter'. Metal was regarded as a combination of scale and phlogiston; in the process of combustion phlogiston evaporated and scale remained. Yet some philosophers believed thermogen itself to consist of a 'fire matter' and 'light substance'. Light was considered a flow of ether particles. Electric and magnetic phenomena were explained by the overflow of fluids, the particles of which acted from a distance.

The theory of imponderable carriers of forces survived up to the beginning of the nineteenth century when it fell in conflict with new experimental and theoretical data. The theory was razed to the ground by the discovery of the principle of conservation and conversion of energy.

The intensive search for and research into imponderable matter and various types of forces resulted not only in the accumulation of new data about the properties of matter (chemical, thermal, electric, magnetic, and so forth) but also facilitated the understanding of fundamentally new forms of matter, motion, and energy.

Thus, for example, between 1772 and 1775 one of the founders of modern chemistry Antoine Laurent Lavoisier (b. 1743, d. 1794) arranged a series of experiments to find the notorious phlogiston. He arrived at the conclusion that combustion occurs owing to a "substance derived from atmospheric air". Experiments conducted in 1774 by the English chemist Joseph Priestley (b. 1733, d. 1804) and the Swedish chemist Carl Scheele (b. 1742, d. 1786) revealed that this 'substance' is ... oxygen. This was the starting point in the evolution of the chemistry of combustion and the development of ideas on chemical energy and principles of its conversion into thermal energy. Soon other gases (including the lightest one—hydrogen) were discovered. The resultant idea was to employ hydrogen's buoyancy in aeronautics. In 1783 the Montgolfier brothers constructed a balloon filled with heated air (the 'montgolfier'), and Charles made a balloon filled with hydrogen (the 'charlier').

Research into thermal phenomena continued. Galileo's thermoscope was succeeded by alcohol and mercury thermometers invented in 1714 by the German Fahrenheit (b. 1686, d. 1736), in 1730 by the Frenchman Réaumur (b. 1683, d. 1757), and in 1742 by the Swede Celsius (b. 1701, d. 1744). The 'force of heat' and the 'amount of heat' were gradually becoming independent notions; the 'force' was measured by temperature, and the amount of heat was the product of the temperature difference by heat capacity and by the amount of the heated material. The new notion of 'heat capacity' expressed the amount of heat required to raise a temperature of a body by one degree. The heat capacity of many solid and liquid bodies was determined and the equation of heat balance (a particular case of the yet unknown principle of conservation of energy) was derived. Fundamentals of heat transfer were developed. Newton's principle of convective heat exchange—the heat exchange between the wall of a vessel and the fluid which touches it—was supplemented by Fourier's principle of heat conduction through a wall (1822).

In 1822 a French mathematician, Jean Baptiste Fourier (b. 1768, d. 1830), published his *Théorie analytique de la chaleur* ("Analytical Theory of Heat") which he believed to bring the theory of heat to the level of mechanics at that time.... However, the theory of thermogen persisted to exist despite all the above-mentioned achievements. Even Lavoisier who had put an end to phlogiston could not dare to part with thermogen which became a major issue of his "Memoir on Heat" written together with Laplace and published in 1783. It was mentioned, however, in the "Memoir" that "other authors believe heat to be an animate force, i.e. the sum of the products of the mass of each molecule by the square of its velocity".

A crucial blow to the theory of thermogen was delivered by the English politician, businessman, and engineer Benjamin Thompson (b. 1753, d. 1814). Having graduated from an American college, Thompson took part in the War for Independence (1775 to 1783) on the side of England, for which he received a peerage. The Bavarian Elector Charles Theodore employed Thompson from 1785 and made him Count von Rumford for his contribution to the construction of factories and efficient heating systems. After the death of the Elector, Thompson returned to England where he founded the Royal Institution headed from 1799 by young Humphrey Davy (b. 1778, d. 1829).

In 1778 Rumford's attention was attracted to the fact that guns were heated more by blank shots than by combat shots, a phenomenon which did not agree with the theory of thermogen. Having too many problems on his hands, he forgot about this one, but twenty years later was faced with a similar situation. Gun barrels were heated in the course of drilling. The shaken Rumford was unable to comprehend where the thermogen was coming from. The assembly was placed in water which boiled in a mere 2.5 hours to everybody's great surprise. The conclusion was irrefutable: heat is motion and not a substance. Soon Davy corroborated Rumford's experiments and attacked thermogen in 1799. The attack was supported by the prominent English scientist Thomas Young and others. By irony of fate, Rumford married the widow of Lavoisier who was guiltlessly guillotined in 1794....

The concepts of electric and magnetic 'fluids' were discarded only at the beginning of the nineteenth century. This, however, did not impede the experimental research which was crowned by the establishment of a measure of electric force and the derivation of correct quantitative dependences. The discovery of electric conduction by the English electrician Stephen Gray (b. *c.* 1696, d. 1736) in 1729, of two types of electricity by the French chemist Charles Du Fay (b. 1698, d. 1739) in 1734, of the first accumulator of electricity (capacitor), the Leyden jar, by the German inventors E. Georg von Kleist (b. , d. 1748) and Pieter van Musschenbroek (b. 1602, d. 1761) between 1745 and 1746, and the discovery of the electric nature of lightning by Franklin in 1750 (corroborated by Lomonosov's and Richmann's experiments) provided more or less true ideas of the nature of electric phenomena. These phenomena had previously been explained by the formation of 'electric atmospheres' around the electrified bodies. This theory was replaced by several others.

A member of the Paris Academy of Sciences, a scientist and engineer, Charles Coulomb (b. 1736, d. 1806), and some other scientists believed in the existence of two different electric fluids of opposite action. A body in a neutral state contains an equal amount of both fluids. Electrization occurs when the amount of one of them exceeds that of the other. Electric and magnetic forces were likened to Newtonian gravitational forces and thus acted from a distance. Hence it was concluded that the value of these forces (similar to gravitational forces) was inversely proportional to the square of the distance between the charges. This, however, was a purely theoretical assumption which required experimental proof. The Leyden jar, the first source of current, provided for more extensive tests. It also stimulated the improvement of electrostatic devices used for its charging and gave rise to the development of measuring technology.

For a long time electric force was measured by its influence on the human body. The French king Louis XV enjoyed watching the influence of the discharge from Leyden jars through a line of soldiers.... But already Gray and Du Fay employed primitive electroscopes consisting of two flax cords suspended from the electrified body. Later elder and cork balls were used for the same purpose. These were replaced by gold leaf in a specially graduated case. It was an electrometer. Yet there was no concrete idea of what electric 'force' was.

The English physicist and chemist lord Henry Cavendish (b. 1731, d. 1810), a prominent scientist but an eccentric and unsociable person who seldom published his findings, was among the first to solve the problem. He carried out a rather sophisticated experiment to measure and determine theoretically electric force, but the results of his experiment were published only a hundred years later by Maxwell....

Charles Coulomb was more generous with his information which was published between 1785 and 1788. He invented a torsion balance in which the angle of the twist of an elastic cord was proportional to the moment of force. The instrument helped him to measure forces acting between two electric charges and to establish the law named after him: the force of attraction or repulsion from the interaction of two electrified balls, and consequently two electric charges, is directly proportional to the product of their magnitudes and inversely proportional to the square of the distance between them. He also established that electricity accumulates only on the surface of conductors and that electric force is directed perpendicular to the surface and is proportional to the density of electricity. Coulomb applied the same law to the interaction of magnets. His works facilitated the development of fundamental notions related to electrostatic and magnetostatic forces: the charge (quantity of electricity), charge density, field of forces, potential, intensity, and others.

The space around a charged ball in which things happened was termed the field of electric forces, or the electric field. This field extends to infinity, but its action rapidly decreases with distance. The work required to deliver the positive charge from infinity to the surface of a positively charged ball was termed the electric potential. This work does not depend on distance (similar to the fall of bodies under the action of gravity). Since work is equal to the product of force by distance, the potential difference divided by the distance between two points is the force at a given point of the field. This force was termed the electric intensity (the current term is the electric field strength).

Thus electric and magnetic forces were no longer 'things in themselves'. The notions of force, work, and energy (in implicit form) were necessary elements, the outlines of which were becoming clearer. A researcher rotating the handle of an electrostatic device to charge the Leyden jar was inevitably and clearly facing the conversion of mechanical 'force' into electric ... and so forth.

Thus the Leyden jar became the first accumulator of electricity, but a source of continuous electric current was yet unavailable. Electrostatics was exhausting itself, and further research was directed mainly at the medical application of the influence of an electric discharge on the human body. Jean Paul Marat (b. 1743, d. 1793), who was assassinated by Charlotte Corday, started his career from this harmless business and even received a prize from the Roanne Academy. Yet his letter to the Paris Academy of Sciences, in which he reported on his experiments in physical therapy and methods of research into fire (he had even developed his own theory of thermogen), light, and electricity, did not receive the attention it deserved. At the same time, the Academy took part then in the activities of a governmental commission which was examining 'works' by Franz Mesmer (b. 1734, d. 1815) who proclaimed that he had discovered a new imponderable matter, 'animate magnetism', which he declared a "universal medicine and savior of humanity", The search in this direction intensified until a professor of anatomy and medicine of the University of Bologna, Luigi Galvani (b. 1737, d. 1798), published a sensational treatise in 1791. Galvani watched the contraction of a frog's muscles in contact with dissimilar metals and arrived at the conclusion that he had discovered a new type of electricity. A test of his results demonstrated that Galvani had discovered an electric current flowing in a circuit consisting of metals and frog specimens, a new source of current (the contact potential difference in metals) and 'animate electricity' (in experiments conducted without metals). The second of the above-mentioned discoveries was corroborated by an ardent follower of Galvani, his fellow-countryman Count Alessandro Volta (b. 1745, d. 1827). The third was proved by Leopoldo Nobili (b. 1784, d. 1835) in 1825.

Volta determined that the farther two metals stand from each other in the 'electromotive series' (zinc, tin foil, tin, lead, iron, brass, bronze, copper, platinum, gold, silver, mercury, graphite), the higher the excitation of nerves. Volta's contact theory helped him to design the first source of continuous current consisting of several tens of silver and zinc or copper and tin plates superimposed on each other and separated by cardboard spacers impregnated with salt water. This achievement brought Volta a decoration from Napoleon and election to the Academy. However, he had no further business with science.... Volta believed that current resulted exclusively from the contact of heterogeneous metals acquiring different voltages, water being a mere conductor. He called his galvanic cell an electromotive organ since an electromotive force (a new force!) occurred where the metals were in contact. This force induced the electricity in the plates to cause a potential difference depending on the nature of the metals.

However, a chemical theory of the action of voltaic pile was soon developed. The theory read that particles decompose in electrolyte (salt water) at the electrodes under the action of the latter on positively charged hydrogen and negatively charged oxygen. The idea belonged to the Lithuanian physicist and chemist Ch. Grotthuss (b. 1785, d. 1822) and the Englishman H. Davy and dated from

1805—long before the discovery of the atom! It is thus not surprising that in 1800 the same Davy and in 1812 the Swedish chemist J. Berzelius (b. 1779, d. 1848) developed, independently of each other, a theory of chemical affinity which read that every atom contains two opposite charges which facilitate the combinability of atoms.

All these findings prepared the way for the direct conversion of chemical 'force' (energy) into electric force. In 1801 Davy constructed the first carbon-oxygen 'fuel cell'. In 1833 the French physicist A. Becquerel (b. 1788, d. 1878) developed a carbon-air fuel cell with melted electrolyte and platinum cathode. Finally, in 1839 the English physicist W. Grove (b. 1811, d. 1896) constructed the first hydrogen-oxygen cell. The efficiency of these transformers should have been double that of thermal engines (theoretically). Yet the general low level of science and technology at that time prevented the realization of this value. The development of fuel cells was resumed only between 1958 and 1960.

To estimate the generated current, one more 'force' had to be introduced: the strength of current or the quantity of electricity passing through the uniform cross section of a conductor per unit time (coulomb per second). This unit was called the ampere after the French scientist André Marie Ampère (b. 1775, d. 1836).

In 1826 the German physicist Georg Ohm (b. 1787, d. 1854) established a law: the strength of current is proportional to the electromotive force and inversely proportional to the resistance of a conductor. The volt became the unit of electromotive force, and the ohm became that of resistance. This law is similar to Newton's and Fourier's laws of heat transfer.

The Russian academician V. V. Petrov contributed much to the research into electricity and magnetism. In 1803 he published a treatise "Information on Galvanic and Voltage Experiments". The experiments were carried out with a battery consisting of 4200 cells (Davy's battery constructed in 1810 was composed of only 2000 cells). Petrov was the first to discover a number of thermal and chemical effects of current, including the electric arc, the electric smelting of metals, and so forth.

But Europe was unaware of his works which were written in Russian....

Thus the understanding of the nature of electric and magnetic phenomena was increasing gradually and related notions of force, work, and energy were developing. Scholars also concentrated on the nature of light; corpuscular, wave, and ether theories were competing. Light was the focus of attention of scientists such as Th. Young, É. Malus, D. Arago, A. Fresnel, P. Laplace, A. Cauchy, J. Gibbs, and others. Some pictured ether as tar, others assumed it was like soapsuds, still others believed it to be caviar-like.... The mechanics of continua was developing thanks to the works of S. Poisson, C. Navier, F. Stokes, and A. Cauchy.

At that time Russia was very much inferior to western countries in science and education, but its leading scholars such as M. V. Lomonosov, V. V. Petrov, as well as L. Euler (he lived in Russia for a considerable period of time), the Bernoulli brothers (they also spent many years in Russia), and others were working on the European level and sometimes even above it despite great difficulties they encountered in their work.

M. V. Lomonosov had a difficult time in the Petersburg Academy, fiercely fighting the inertness and dominance of bureaucrats in science. He told the academician Shtelin before his death:

"My friend, see that I'm dying and I face death quietly and indifferently. I only wish I could have accomplished all I have undertaken for the benefit of my country, the development of science, and the glory of the Academy. It is a pity that at the end of my life I have to see how all my useful intentions will perish along with me."

The situation changed very little even 150 years later. The great Russian physicist P. N. Lebedev wrote bitterly in 1912, several months before his death, about the unbearable working conditions in Russia, which were very much like those criticized by Lomonosov. A dreadful number of creative ideas were perishing but still much was achieved regardless of those conditions....

Destruam et aedificabo

The advocates of the theory of 'imponderable' matter broke nature down into elements while neglecting the interrelationships between natural phenomena. These interrelationships were being corroborated by an increasing number of facts. The time had come to start reasoning by a well-known Latin principle: *destruam et aedificabo*—'I will destroy and construct'. A good thing would have been to construct a uniform theory of all phenomena, but this is hard to accomplish even presently.... When physicists have difficulties, idealistic philosophies multiply, for speculative reasoning is much easier than searching for the truth. The popularity of Kant, Hegel, and Schelling was increasing. However, despite the futility of many of their ideas, all these philosophers were then fervently advocating the concepts of universal relationships between phenomena and forces, thus contributing to the progress of science.

Professor Hans Christian Oersted (b. 1777, d. 1851) of the University of Copenhagen supported the above-mentioned idea (thoroughly developed by Schelling) and searched intensively for a relationship between electricity and magnetism, although it was a firm belief from the times of Gilbert that nothing of the kind existed. Having discovered this relationship (on the 21st of July, 1820), he communicated to all scientific institutions and magazines his treatise "Experiments on the Action of the Electric Conflict on the Magnetic Needle" in which he stated: "Galvanic electricity passing from north to south above a freely suspended magnetic needle deflects the north end of the needle to the east, and if passing under the needle deflects it to the west."

Oersted's experiments revealed a new type of interaction, a new source of mechanical motion, the motive power of electricity, and a new technique for measuring electric current. His discovery seemed to have broken through the dike, impeding the progress of long-collected facts which were awaiting explanations. Further development resembled a detective story. On the 4th of September the French astronomer and physicist D. Arago (b. 1786, d. 1853) reported this discovery at a session of the Paris

Academy of Sciences at which Ampère (who was also looking for common features in natural phenomena) was present. A week later Arago demonstrated Oersted's experiment before the members of the Academy, and on the 18th of September Ampère delivered a report on electromagnetism and its possible interpretation. On the 25th of September Ampère reported on his experiments and the discovery of the interaction of currents, and Arago reported the discovery of magnetization by current. On Ampère's advice he carried out magnetization with the help of a solenoid, a glass tube on which a wire was coiled to conduct electric current. A needle was positioned inside the tube. Thus the principle of the electric magnet was discovered!

Ampère conducted a comprehensive research into the interaction between current and magnet and the interaction between currents. He suggested that the new phenomena should be termed electrodynamic and the old ones electrostatic. He made magnetism a branch of electrodynamics and treated magnetic interactions as interactions of circular currents. Circular current is identical to a thin flat magnet, the sides of which are its poles. On the 30th of October Ampère reported new evidence in support of his theory: a freely suspended solenoid positions itself in the magnetic field of Earth exactly as the magnetic needle does. Thirty years later Maxwell said about him: "Theory and experience seemed to have flowed spontaneously in full strength and completeness from the head of the 'Newton of electricity'!"

Scientific achievements in the study of electromagnetism were immediately put into practice. Already in 1825 the Englishman W. Sturgeon constructed an electromagnet, and in 1832 the American physicist Joseph Henry (b. 1797, d. 1878) operated a magnet with a lifting capacity of 2 tonnes.

The next stage in discerning the universal relationships between phenomena and forces or, as we would say today, in the conversion of certain forms of energy into others, was the discovery of the possibility of converting thermal 'force' (energy) into electric force.

The German physicist Thomas Seebeck (b. 1770, d. 1831) did not accept Ampère's explanation of Oersted's experiment. He was looking for another interpretation and discovered that by putting wires made from dissimilar metals into contact a magnetic needle is deflected. This implied that both Oersted and Ampère were right because Volta had already determined that when dissimilar metals come in contact, current begins to flow. Having thoroughly checked everything. Seebeck found that a magnetic needle is deflected if the junction is warmed by hand. To make sure, he heated the junction on a spiritlamp—the result was the same. Yet Seebeck failed to believe in the interaction between current and magnet. He termed the discovered phenomenon 'thermomagnetism' and immediately developed a 'theory of terrestrial thermomagnetism' conditioned by the 'temperature difference between the poles and equator', the latter being surrounded by an area of metals and ores heated by volcanoes.... Seebeck campaigned for his alleged 'discovery' and against the real one for two years. During this time he conducted a multitude of experiments, made a classification of metals according to their 'magnetism', determined the forces induced by the temperature difference at the ends of a homogeneous conductor, and so forth. It is worth mentioning that if he had attempted to use his device to produce electric current with the help of two metals occupying the extreme positions in his classification line, the efficiency would have amounted to about 3%, which is equal to that of the steam engines of the time, but the design of such a device would have been much simpler....

The French watchmaker Jean Peltier (b. 1785, d. 1845) was a stubborn person. He persisted in his attempts to disprove the law which read that heat is released when current flows through a conductor, i.e. electric 'force' (energy) converts into thermal force. Peltier experimented with the same materials Seebeck used: first with bismuth and copper, then with bismuth and antimony. He soldered plates at one end and applied current to the other. The effect was a heating or cooling (depending on the direction of the current) of the junction by 5 to 10 degrees in the first case and by 40 degrees in the second. Peltier assumed this to result from the different values of the electric conduction of metals. The experiment dated from 1834, and in 1838 the Petersburg academician Heinrich Lenz (b. 1804, d. 1865) carried out a spectacular experiment (a 'crucial experiment' under Bacon's classification) which supplied an exact answer. He made a hollow at the junction of the bismuth and antimony rods and placed a drop of water there, which froze or melted depending on the direction of the current. This implied that heat was taken away from the drop in the first case and supplied to it in the second. The effect was opposite to that of Seebeck.

Contemporaries did not realize the full importance and value of the above-mentioned discoveries. The manufacturing of the first thermoelectric generators, refrigerators, and heaters started only in 1958-1960.

The public was also skeptical about theories developed by the great experimentalist Michael Faraday (b. 1791, d. 1867) because he "failed to get a higher education". Indeed, the son of a smith from a London suburb had studied only bookbinding. It was a mere coincidence that he attended once a lecture delivered by Professor Davy. The 21-year-old bookbinder was so impressed by the lecture that he turned to the professor for employment as his secretary and assistant. His progress was so rapid that by the time he was 25-year-old Faraday was already publishing articles on chemistry, which activity met no friendly welcome from the professor. Then Faraday turned to electromagnetism. The achievements of the young man were so notable that at the age of 33 he was elected a fellow of the Royal Society against the desperate resistance of the Society's Chairman ... H. Davy. 'C'est la vie!'

Strange as it may seem, Faraday's theoretical ideas guided him to great experimental discoveries. He was firmly convinced in the universal relationships, unity, and interconvertibility of phenomena and forces. Having rejected the idea of fluids, he defined electric current as an "axis of forces on which identical forces are oppositely directed". This was a purely mathematical definition. He also denied 'remote action' since matter (in his theory) occupied all of space and was a carrier of the forces of repulsion and attraction. In 1823 Faraday wrote in his diary: "I must turn magnetism into electricity," which meant to turn magnetic force into electric force. He pursued this objective for eight long years moving slowly, hour by hour, day by day, year by year. He observed induction—the action of force 'through influence'—first during an experiment with two coils of copper wire one inside the other but without a contact between them. When current was switched on and off in one coil, the needle of a galvanometer connected to the other coil was deflected. Faraday wrote: "Current from a battery flowing through one conductor does induce a similar current in the other conductor but ... this current continues only for a moment."

This enabled Faraday to explain phenomena which had occurred in the experiments by other scientists, including the 'magnetism of rotation' discovered by Arago several years earlier. Faraday developed the idea of short-range interaction to introduce magnetic lines of force, which he had discovered during experiments with iron filings, and related them to the law of electromagnetic induction. This law stated that the electromotive force induced in a circuit by a changing magnetic field is equal in magnitude and opposite in sign to the rate of change of the magnetic flux linking the circuit. When current starts to flow in the inducing conductor, a motion of 'magnetic curves' sets in "...from the moment when they begin to develop to the moment when the magnetic force of current attains its maximum value; they seem to spread sidewards from the wire and thus take the identical position in relation to the motionless induced wire as if it were moving in the opposite direction across them or in the direction of the current-carrying wire". This is the first description of an electromagnetic field and the first indication of the spread of magnetic disturbances in time. The practical value of the discovery was equally high: a mechanoelectric generator of electric current succeeded the galvanic (chemicoelectric) and thermoelectric generators and saved the way for a large family of modern electric devices.

Faithful to the idea of the interconvertibility of forces, Faraday thoroughly investigated the chemical action of electric current and established that one and the same quantity of electricity liberates an amount of a simple substance proportional to its chemical equivalent. He carried out experiments to prove the identity of currents induced by different sources and derived one more law: chemical force, similar to magnetic force, is directly proportional to the absolute quantity of flowing electricity.

The first mathematical theory of electromagnetism was developed by the German mineralogist, physicist, and mathematician Franz Neumann (b. 1798, d. 1895) between 1845 and 1847 on the basis of the concept of remote action which was dominant at that time. The theory was improved by the German philosopher, physicist, and psychologist Gustav Fechner (b. 1801, d. 1887) and the German physicist Wilhelm Weber (b. 1804, d. 1891). Yet it was contrary to many facts and had to be retracted in 1862 under the pressure of a genial theory developed by James Clerk Maxwell (b. 1831, d. 1879).

Maxwell furnished Faraday's experimental results with a mathematical interpretation based on the concept of short-range interaction—the mechanical motions in all-penetrating ether. Having endowed ether particles with a multitude of specific properties and motions, he, however, did not regard them as a physical reality; it was a mere analogy, a model. This model enabled him to derive six famous equations describing the electromagnetic field of forces and to discover its new properties and the velocity of electromagnetic waves, which appeared to be equal to the velocity of light. This was a sensation! Experiments by the German physicist Heinrich Hertz (b. 1857, d. 1894) proved the identity of 'electric force rays' and light rays.

Thus the idea of the universal relationships between phenomena and forces was generally recognized. Heat, electricity, magnetism, chemical and mechanical phenomena, electromagnetism, and light (one of the forms of electromagnetism) mutually affected and could generate each other. Causalities and quantitative dependences were firmly established. The remaining task was only to give abstract definitions common for all phenomena (scientific notions of force, work, and energy) and to formulate a universal law of their quantitative relations, qualitative varieties, and the interconvertibility of the latter. The situation was similar to that which existed 100 years earlier, before the publication of Newton's works....

The Principle of Conservation and Conversion of 'Forces' (Energy)

The triumvirate of Force, Work, and Energy reigned over the world openly or secretly, in accord with or against the will of naturalists. They either took turns, or performed specific functions, or disturbed one other. The system required a tidying up.

The challenge was answered by Lazare Nicolas Carnot (b. 1753, d. 1823), a member of the Paris Academy of Sciences, a prominent leader of the French Revolution, a member of the Committee of Public Safety, a minister who had organized 14 armies which defended France against all Europe. They say that Napoleon told him after the defeat at Waterloo: "Mr. Carnot, I regret that I have met you too late." In 1783 Carnot published a treatise *Essai sur les machines en général* ("Essay on Machines in General") in which he treated work as the product of force by velocity and time, and used terms such as 'moment of action' and 'activity' which he considered identical. But in 1803 he replaced velocity and time by the distance traversed by the point of application of force, and demonstrated that the amount of work performed should be equal to the change in the 'animate force'. He believed the 'animate force' to play an important role in the theory of engines; it was conserved to make full use of its potential. He suggested that the efficiency of machines should be measured by the loss of the amount of the 'animate force' resulting from friction or collision. He assumed that the loss was dependent on the rate of change of velocity.

In 1808 the prominent English scientist (as well as tight ropewalker and circus rider) Thomas Young (b. 1773, d. 1829) published a collection of lectures in which he wrote: "In almost all cases of the application of forces in practical mechanics, the work expended to produce motion is proportional not to the moment but to the acquired energy." By 'energy' he meant the 'animate force'. It was the first clear interpretation of these notions.

In 1829 the French academician Gaspard de Coriolis (b. 1792, d. 1843) published a "Treatise on Mechanics" in which he replaced the expression of 'animate force' as $m\omega^2$ by $m\omega^2/2$ and wrote:

"...I have termed 'work' the quantity which is traditionally called mechanical power, the quantity of action, and dynamic effect. The word 'work' is so natural in the meaning I associate it with that, although it was never used as a technical term, it was nevertheless used by the French engineer Claude-Louis-Marie Navier (b. 1785, d. 1836) in his notes on Belidor and Prony in 'Memoirs'."

Another French academician Jean Poncelet (b. 1788, d. 1867) used the notion of 'work' as early as 1826. The principles of conservation of work and conservation of 'animate force' were equivalent in his theory.

In 1824 a lieutenant of the French General Staff, Sadi Carnot (the son of Lazare Carnot), published a treatise "On the Motive Power of Fire and Machines Capable of Producing This Power". The event had been anticipated for 1900 years since the times of Hero of Alexandria! Carnot expected thermal machines to "bring about a great revolution in the civilized world". His objective was to disclose the reasons for the low efficiency of heat engines. Carnot formulated the theorem: "The motive power of heat does not depend upon the agents taken to produce it; its quantity is determined exclusively by the temperatures of bodies between which, in the final analysis, the transfer of thermogen takes place." (Posthumous notes by Carnot revealed that he soon discarded thermogen and turned to the mechanical theory of heat much earlier than other scholars did.)

Carnot determined the conditions required to obtain maximum work when two sources of heat, hot and cold, form the working cycle. If there is no loss of heat during its supply from the heater (heat source) to the 'agent' (gas, for example) and during its withdrawal from the agent to the cooler (heat sink), both these processes should pass at constant temperatures (isothermally) equal to the respective temperature of each of the bodies. In the absence of any other sources of heat, the 'agent', the modern term for which is the 'working medium', may pass from one temperature evel to another only without heat exchange, i.e. adiabatically. These four processes form a rectangle on the temperature-entropy plane which represents the famous ideal cycle of the heat engine (Carnot cycle). Carnot wrote that the efficiency of this cycle (i.e. that of the ideal heat engine) should be proportional to temperature $t°$ if a unit of thermogen 'falls' from $t°$ to 0° C, i.e. $\eta_C = Ct$, where C is an unknown function of the temperatures of a heater and a cooler. This was called the 'Carnot function' until it was established that $C = 1/T_1$, where $T_1 = 273 + t_1°$ is the absolute temperature of a heater. The modern Carnot formula has the form $\eta_C = (T_1 - T_2)/T_1$, where T_2 is the absolute temperature of a cooler.

Carnot's work contained no mathematical dependences and passed unnoticed. It became a sensation only ten years later after the publication of the treatise "On the Motive Power of Heat" by the French engineer Benoit-Paul-Émile Clapeyron (b. 1799, d. 1864), a member of the Paris Academy of Sciences and corresponding member of the Petersburg Academy of Sciences. Clapeyron 'translated' Carnot into the language of mathematics, having thereby demonstrated the great internal potential of Carnot's work. He was the first to investigate the operation of heat engines with the help of a graphical method. Clapeyron calculated the amount of work as the square area under the curve of the process on the pressure-specific volume plane. However, Clapeyron also failed to derive the Carnot formula for efficiency in its modern form.

Mathematicians and theorists of physics, such as Euler, Lagrange, Laplace, Poisson, Green, and Hamilton, approached the exact definition of the notions of 'work' and 'energy' in their works on statics, dynamics, and potential theory. Thus, in 1828 a former baker, George Green (b. 1793, d. 1841) published an "Essay on the Application of Mathematical Analysis to the Theory of Electricity and Magnetism" in which he introduced a notion of potential function or simply of 'potential' and expressed the latter mathematically (Green's formulas), which he applied to electrostatic and magnetostatic problems. The notion of 'potential' soon became very popular. But since the potential difference between two points of an electric field defines the work performed when a charge moves from one point to the other, the potential itself is, in fact, the potential energy of the body at the given point of the field.

Between 1834 and 1835 the prominent Irish mathematician Sir William Rowan Hamilton (b. 1805, d. 1865) published the article "General Methods of Dynamics" in which he determined motion in terms of variables and new functions, while formulating a general principle of least action. The 'principal' function is that of initial and final coordinates and time, and is equal to the sum of 'animate forces' (T) and 'tension forces' (P). The latter are called the force function for stationary (i.e. unaltering with time) conservative systems (mechanical systems, the motion of which gives a constant sum of $T + P$) and express the total energy of the system.

This was the situation shortly before the final formulation of the principle of conservation of ... no one knew what: force, work, or energy. While scientists were racking their brains over this problem, the family of steam engines continued to grow in number and improve in design. Engines constructed in 1828 consumed 17 times less fuel than the first engines manufactured by Watt. In 1807 Fulton's first steamer started the navigation on the Hudson; communication by steam vessels began to develop rapidly. In 1825 the first railway served by Stephenson engines was opened in England. In France and Germany railways appeared in 1832 and 1835 respectively. The first Russian engine was constructed by the Cherepanovs—father and son—serfs of a mighty Ural businessman, Demidov, but the engine's boiler exploded at the first moment of operation. In 1834 the same Cherepanovs put into operation another engine along with the 2795-feet-long railway. In 1837 the railroad connected Petersburg and Tsarskoe Selo (the summer residence of Russian tsars).

The achievements of physiology and chemistry were also of no minor importance. It became clear that there is no mysterious 'animate force', and the human organism is a special kind of chemical laboratory. Thus it was not by chance that the major contribution in formulating the principle of conservation of energy was made by the German physicians Julius Robert von Mayer (b. 1814,

d. 1878) and Herman Ludwig von Helmholtz (b. 1821, d. 1894). But before them a Petersburg academician, J. H. Hess (b. 1802, d. 1850), had discovered the law which read that the amount of liberated heat does not depend on the type and number of intermediate chemical reactions but depends upon the original and final reaction products. This was, in fact, the principle of conservation of energy in chemical reactions.

The first formulation of the principle of conservation and conversion of 'forces' (however a rather incomplete one) was given by Mayer in the article "On the Quantitative and Qualitative Estimation of Forces" which he sent to *Physical Records* on the 16th of July, 1841. The article was not printed, and the author was not even acknowledged with a reply. Another article, "Notes on the Forces of Inanimate Nature", was published in the *Chemical and Pharmaceutical Records* (a magazine edited by J. Liebig) in May, 1842. The titles of the articles said nothing about their importance; the text also failed to reveal the full value of the content. This is no wonder since Mayer's background in physics and mathematics was inadequate. The young physician who dared to touch upon the vital problems of physics was brought up in the family of a druggist in Heilbronn and studied medicine at the University of Tübingen where the famous Gmelin lectured in chemistry, but mathematics and physics were not taught. Mayer was arrested for membership in an 'unlawful society' (the student circle "Westfallen"), but was released after six days of a hunger-strike and expelled from the University. He moved to Munich and then to Vienna to complete his education. In 1838 he received permission to return to Tübingen where he got his doctorate of medicine. Having no wish to become an obscure 'petty physician' in his native town, Mayer applied for employment as the ship's physician on the Dutch vessel "Java". Being an observant person, he was impressed by the navigator's statement that water temperature raises during a storm. Mayer had to perform numerous phlebotomies in Surabaja where an epidemic of pneumonia had broken out. He noticed then that in the tropics the venous blood is almost as light as the arterial blood. This led him to the conclusion that there is a similarity between the human organism and the steam engine. He assumed that at high atmospheric temperatures the human organism consumes less food ('fuel'), or heat, hence the amount of liberated carbonic acid, or 'smoke', decreases, which makes the venous blood lighter in color. The hypothesis implied a certain relation between work and heat in general.

After his return to Heilbronn in 1841, Mayer began writing his first article of which he informed his Paris acquaintance, the prominent mathematician and physicist Bauer. Mayer related the idea of conservation of forces to the well-established principle of conservation of substance (mass) in chemistry. He wrote: "We must apply absolutely the same principal laws to forces; the latter, similar to substance, are indestructible, they form various combinations with each other, lose their previous form ... but take on a new one.... Forces ... are motion, electricity, and heat." Yet Mayer erroneously treated momentum $m\omega$ instead of the 'animate force' $m\omega^2/2$. He, however, corrected this mistake in his second article and gave a more clear interpretation of 'forces' and their conversions. Forces are causes, he said, and have thus a direct relation to the following axiom: "Cause is equal to action. Causes are (quantitatively) indestructible and (qualitatively) convertible imponderable objects, which means that forces are indestructible and convertible imponderable objects."

Thus the traditional and tenacious concept of imponderability was transported from matter to forces, having thereby opposed ponderable matter to imponderable forces. Mayer distinguished between the force proper and 'force' (energy), although he did not use the latter term. He stated that a fall of a body requires its 'lift', i.e. force, no less than 'gravity', which is given by $mgh = m\omega^2/2$, where g is the acceleration due to gravity, and h is height. "We have obtained," he wrote, "a principle of conservation of animate forces based on the general principle of the indestructibility of causes." Hence he proceeded to the question: "What further form can be adopted by the force which we have comprehended as the force of fall or motion?" He arrived at the conclusion that this form was heat "generated by motion"; yet "motion should cease to be motion in order to become heat". This inaccuracy invoked sharp criticism by the British mathematician and physicist Peter Tait (b. 1831, d. 1901) and others who denied Mayer's priority in the discovery of the principle of conservation of energy and the development of the mechanical theory of heat.

Mayer's words cited above plainly indicate the polysemy of the term 'force' at that time. 'Gravity' is the force proper, 'force of fall' is the potential energy of a lifted body, 'force of motion' is the kinetic energy, and the product of 'lift' (height) by 'gravity' is equal to the force of fall and is the work related to gravity in its modern meaning.

Mayer also calculated the mechanical equivalent of heat to be equal to 365 kgf-m/kcal (which is currently assessed at 427 kgf-m/kcal). Mayer based his calculations on the tentative theoretical conclusion that the heating of one kilogram of gas by one degree requires the quantity of heat at constant pressure, c_p, exceeding the quantity of heat at constant volume, c_V, by the amount of work ('gas constant') R, which is given by the equation: $c_p = c_V + R$. If the efficiency of our best steam engines, he wrote, were compared to this result, we would see that only a small part of heat supplied to the boiler is converted into motion or lifting of weight.

If Mayer had had a better background in physics and mathematics and had taken the trouble to study works by other researchers, his conclusions would have been more clear, and specialists would have given them more credit and attention. Mayer's work was preceded (or paralleled) by the works of C. F. More and the Danish physicist Ludwig Colding.

In 1841 the famous English physicist James Prescott Joule (b. 1818, d. 1889), a brewery-owner from Manchester, started his scientific career after which science became his life-long occupation. Between 1841 and 1843 Joule conducted a series of experiments to determine the thermal effect of electric current. In the course of experiments he succeeded in calculating the value of the 'mechanical equivalent of heat'. His result was 460 kgf-m/kcal, which is much closer to the real value than that of Mayer. This was accomplished with the help of a device which has become a classic unit: water was heated in a barrel by the rotation of paddles, and then the relation of expended work to obtain heat was calculated. This, however, expressed only the relationship between different units of measurement of energy and not the value of a certain 'equivalent' because the principle of conservation reads that the amounts of interconverting forms of energy should be equal. Yet even presently the mechanical equivalent of heat is treated in many university textbooks....

Meanwhile, nobody knew that works by S. Carnot (who died in 1832), some of which were published in 1878 and the rest awaited publication until 1927, contained a mechanical interpretation of heat, the definition of mechanical equivalent, the formulation of the principle of conservation of 'force'....

Mayer was greatly disappointed by his article having not received the attention it deserved (he had assumed it could not have failed to shake the world of science) and wrote one more paper "Organic Motion in Relation to Metabolism". This time Liebig refused its publication, and Mayer had to publish it with his own money in the form of a booklet. Having refined the ideas formulated in his first two articles, Mayer proceeded to treat five different forms of force of motion: mechanical motion, force of fall, heat, electricity, and chemical 'difference'. He described 20 variants of their interconversions, proceeding from the idea that 'force' remains a constant value in all chemical and physical processes. He also investigated conversions of the 'force of the Sun' on Earth. "The flow of this force," he wrote, "is that continuously wound-up spring which keeps the mechanism of all terrestrial activities in a state of motion." Mayer called for a study of the mechanism of light absorption by plants (the idea was realized later by Timiryazev), he attacked the theory of 'animate force' supported by Liebig (that is why Mayer was refused publication in Liebig's magazine), he stated that the consumption of oxygen and food in organisms results in chemical processes having thermal and mechanical effects. In 1848 he wrote "Celestial Dynamics" in which the assumption was made that the Sun's mass decreases with radiation....

Mayer's articles passed unnoticed or were criticized despite the progressive ideas contained therein. This may have been why Joule did not mention Mayer in his report on experiments published in 1847, which brought an indignant protest from Mayer. Joule replied that Mayer had only predicted the existence of the mechanical equivalent of heat but had not defined it.

The argument was still going on when another medic and physiologist Hermann Helmholtz wrote a treatise "On the Conservation of Force". The 'animate force', which was previously believed to control physico-chemical processes in organisms ('perpetual motion machines'), was expelled from science. However, he was also refused publication in *Physical Records* on the grounds of the "excessive volume and theoretical character of the work". Yet it was hard to discourage Helmholtz. He published the book at his own expense, and the publication turned out a rather profitable investment. Helmholtz derived his principle of conservation of 'force' from a multitude of examples. In contrast to Mayer's articles, the book attracted the attention of scientists, but their reaction was rather unexpected. The majority of physicists criticized this principle. Helmholtz's idea was supported only by the German mathematician Karl Jacobi (b. 1804, d. 1851) and members of a newly formed Physics Society (Berlin).

Helmholtz proceeded from the assumption that all things consist of material particles between which the 'central forces' (the "forces of attraction and repulsion, the magnitude of which depends upon distance") act. Mechanics had already developed the principle of conservation of 'animate forces' for such systems. Having introduced the notion of 'tension forces'*, Helmholtz extended this principle to a principle of conservation of the sum of 'animate and tension forces'. He considered this principle applicable to any material processes, including those taking place in living organisms. This formed the mechanistic background for his research into mechanical, thermal (heat as the motion of particles), chemical, gravitational, elastic, electric, and magnetic 'forces'. He formulated a mathematical expression for each of them and de-

* Potential energy.

termined an absolute measure—the amount of work—which Mayer failed to do. This approach eliminated the qualitative differences between various types of 'forces'. Moreover, the notions of 'force' such as energy and the force proper differed less in Helmholtz's theory than in Mayer's, although Helmholtz accepted the inseparability of 'forces' and motion from matter. His analysis of non-mechanical 'forces' such as electric, magnetic, chemical, and thermal is of special significance. "All the innumerable acting causes in nature," wrote Engels, "which had hitherto led a mysterious inexplicable existence as so-called forces ... have now been proved to be special forms of ... energy...."

Distrust in the new principle was soon mitigated by William Thomson (Lord Kelvin), Rudolf Clausius, and William Rankine. In 1853 W. Thomson introduced the following definition of energy: "The energy of a material system in a certain state is the sum of all actions, measured by mechanical units of work, which take place outside the system when it passes by any way from this state to an arbitrarily selected zero state." This definition contains, in fact, two characteristics of energy which are currently encountered, i.e. energy as a function of the state of the system and energy as a measure of the efficiency of the system. However, they are insufficient since the total energy of a system depends upon external actions, and efficiency can be determined only in relation to an arbitrary zero state of the system. Thus Engels and his followers defined energy as a measure of motion of matter with a qualitative conversion of the forms of motion (types of energy), and work as an "alteration of a form of motion treated quantitatively". The discovered principle signalled that "...for the first time the qualitative content of the process comes into its own, and the last vestige of a supernatural creator is obliterated" (Engels).

The principle was firmly established, and the argument about priority was reaching its climax. Thus Helmholtz declared that he "knew very little about Joule's experiments and absolutely nothing about Mayer's works" when he was preparing the publication of his booklet. But, in fact, in 1845 he made a synopsis of Mayer's "Organic Motion..." for the Physics Society, and his conclusion that the paper was insipid turned readers away from it. It is thus not surprising that even Clausius became acquainted with Mayer's works only after 1862, and before that he had been firmly prejudiced against them. He wrote later: "...I have realized that Mayer had manifested his views so thoroughly and clearly and developed such a wealth of ideas that he had to be perplexed when even some of his conclusions were argued. I have withdrawn my former opinion...."

In his report "On the Interaction of the Forces of Nature" made in 1854 Helmholtz mentioned the contribution of Mayer as the one who was "the first to understand and formulate correctly the principle of conservation of force" as early as 1842. Yet very little changed in Mayer's life even after that. The badgered and lonely Mayer attempted suicide in May, 1850. Having jumped out of the window, he remained alive but was left with a lame. In 1851 he published "Notes on the Mechanical Equivalent of Heat" which was a reply to his opponents. "This apology," wrote Ostwald later, "seems to have been written with Mayer's blood and has exhausted his last forces." Indeed, Mayer developed a disease similar to an inflammation of the brain, and his relatives—for whom the scientist was a constant inconvenience—immediately committed him to a mental hospital. A rumor was spread that he died there, but he was out of the hospital in 1853. Mayer resumed his scientific activities in 1862, but failed to add anything significant to his former contributions.

In 1872 E. Dühring published "A Critical History of the Principles of Mechanics" in which he lauded Mayer's work and disparaged the services of Joule and Helmholtz. Helmholtz could not let Dühring get away with this and secured the latter's dismissal from the University of Berlin, launching a campaign of unfair attacks against Mayer.

Thus the principle of conservation and conversion of energy was established by two physicians and a brewer who had nothing to do with numerous scientific institutions full of academicians, doctors, professors, masters, bachelors.... It was very wise of Pythagoras to say that knowledge cannot substitute for intellect....

The Multifaceted Queen

Oh, Nature is a sphinx and thus for sure
The ordeal by it is perilous for us,
Because there is a reasonable chance
Its mystery was ever dwarfish and obscure.

F. Tutchev

How Many Faces Does Her Majesty Have?

120 years ago Engels said:

"That momentum (of the so-called energy) remains unaltered when it is transformed from kinetic energy into electricity, heat, potential energy, etc., and vice versa, no longer needs to be preached as something new: it serves as the already secured basis for the *now much more pregnant investigation into the very process of transformation, the great basic process, knowledge of which comprises all knowledge of nature.*" (Italics are mine—*G.A.*)

But what is the range of these transformations—what are the forms of energy and how many of them exist? Even Engels, who had formulated the problem and contributed much to the classification of sciences and forms of motion, did not answer this question. Surprisingly, this issue remained untouched from then on. Moreover, one could hear occasional voices calling for the abandonment of the notion of a 'form of energy'. Yet it is now absolutely clear that a general classification should be a compulsory part of any scientific investigation. The discovery of common features in various objects and phenomena, the systematization of them and relation to the classes of the known and unknown are all parts of a universal method of scientific prognostication. It means that classification provides the means to predict new facts and phenomena. Its 'heuristic' function is not incidental since classification proceeds from knowledge and reflects the regular relationships between real general and specific features of the examined objects of our environment, That is why Einstein indirectly supported the idea of the classification of the forms of energy. Thus he wrote that *energy* depends also on parameters characterizing thermal, electric, chemical, etc., properties of the system.... "Modern physicists," he continued, "also consider the reduction of all forms of energy to a singular one to be a significant progress, but they don't hope to accomplish this task in the nearest future." Further, Einstein gave an example which showed that this is not a question of 'terminology', as some were inclined to believe, because the adopted "assumption *will lead to ... further conclusions and research* (italics are mine—*G.A.*) to which the initial assumption would have never led".

Physicists must have realized this when the principle of conservation of energy was yet in the process of being established. Thus in 1842 the British physicist Sir William Grove (b. 1811, d. 1896) was one of the first to divide 'forces' into motion, heat, light, electricity, magnetism, and 'chemical affinity' (a force of chemical elements which causes them to interact). Helmholtz and Gibbs demonstrated later that chemical affinity is determined by the free energy* of the system, i.e. by the portion of total energy which can be converted into work under the given environmental conditions. As we have seen, Helmholtz classified Mayer's 'forces'—gravitational, mechanical, thermal, magnetic, electric, and chemical—into 'tension' and 'animate' forces (including the elastic force). The Scottish engineer and physicist William Rankine (b. 1820, d. 1872) used another terminology. He classified energy into 'potential' and 'actual' and added 'radiant heat', light, and 'static electricity' to Helmholtz's classification. It is worth mentioning that Feynman's famous lectures published 100 years later added only nuclear energy and the 'energy of mass' to this classification....

These stormy 100 years, however, were rich in events. Maxwell formulated the 'great equations' of electromagnetic field and discovered the electromagnetic nature of light. The same Maxwell, together with Boltzmann, Thomson, and Clausius, developed a molecular-kinetic theory of gases. Works by Carnot, Mayer, Helmholtz, Clausius,

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* This notion will be treated below.

Thomson, Planck, Gibbs, and others formed the basis of thermodynamics—a universal method of investigating processes which take place in macrosystems. Umov developed ideas about the localization of energy and the velocity of its motion in space. The structure of the atom and nucleus was determined, techniques of fast- and slow-neutron fissions were discovered, which were accompanied by an immense release of energy. All began with an unplanned coincidence.

In 1896 the French scientist A. Becquerel noticed that uranium salt had spoiled a photoplate through black paper. As it turned out later, he had discovered natural radioactivity. Two years later the Parisians Marie Curie (neé Marja Sklodowska) (b. 1867, d. 1934) and Pierre Curie (b. 1859, d. 1906) discovered two new radioactive elements: polonium and radium.

In 1900 the German physicist Max Planck (b. 1858, d. 1947) laid the foundation of quantum mechanics, and in 1905 the American physicist Albert Einstein (b. 1879, d. 1955) introduced the fundamentals of the theory of relativity and demonstrated that energy is proportional to mass, which is given by $E = mc^2$.

In 1911 the British physicist Ernest Rutherford (b. 1871, d. 1937) proposed a planetary model of the atom and proved that all its mass is concentrated in the nucleus. Two years later the Danish physicist Niels Bohr (b. 1885, d. 1962) created a model of the hydrogen atom and worked out a theory of atomic structure. This was the start of the rapid progress of quantum mechanics and nuclear physics. However, no one was looking for ways to accomplish nuclear fission. Rutherford denied the very possibility of it....

In 1930 the German physicists Walther Bothe (b. 1891, d. 1957) and H. Becker, and in 1932 the French researchers Irène (b. 1897, d. 1956) and Frédéric (b. 1900, d. 1958) Joliot-Curie bombarded light elements (boron and beryllium) with alpha particles (helium nuclei), which had escaped from polonium, and knocked out of them other particles including some unknown uncharged heavy ones which were defined exactly and termed 'neutrons' by the British physicist Sir James Chadwick (b. 1891, d. 1974). In 1932 the Soviet physicist D. D. Ivanenko also introduced hypothesis of the structure of the atomic nucleus which he regarded as consisting of protons and neutrons. In 1933 the Joliot-Curies discovered artificial radioactivity. They bombarded boron and aluminum with alpha particles and thereby obtained new radioactive elements: isotopes of nitrogen and phosphorus.

In 1934 the Italian physicist Enrico Fermi (b. 1901, d. 1954) began to bombard uranium, the heaviest element, with neutrons and obtained transuranium elements which he believed were heavier isotopes having an atomic number greater than that of uranium (92). This was caused by the uranium absorbing the neutrons. In 1935 I. V. Kurchatov, B. V. Kurchatov, L. I. Rusinov, and L. V. Mysovsky exposed isotopes of boron to neutrons to discover nuclear isomerism: they obtained three isotopes of boron out of two. In 1935 Kurchatov published "Splitting of the Atomic Nucleus" which reviewed the achievements in this field.

In 1938 experiments by Otto Hahn (b. 1879, d. 1968) and Fritz Strassmann (b. 1902, d.) in Germany, Irène Joliot-Curie and Pavle Savic (b. 1909, d.) in France, Lise Meitner (b. 1878, d. 1968) and Niels Bohr in Denmark demonstrated that the new elements obtained in experiments by Fermi are not heavier but lighter than uranium and are its disintegration products. It was also discovered that two or three new neutrons are formed per each starting neutron, and the energy released exceeds that of coal by 2.5 million times. In the USSR theoretical research and calculations were made by Ya. I. Frenkel, Yu. B. Hariton, Ya. B. Zeldovich, and experiments were carried out by G. N. Flerov, K. A. Petrzhak, and others.

In December, 1942 the first atomic reactor was commisioned in Chicago. The work was headed by E. Fermi who had escaped to the USA with a group of European physicists. In July, 1945 the first atomic bomb was tested in the USA, and in August American bombs fell upon Hiroshima and Nagasaki.

In the USSR the research into atomic problems which had been interrupted at the start of the war was resumed in March, 1943. The work was headed by I. V. Kurchatov, and in December, 1946 a chain reaction of uranium fission was carried out at the Moscow Institute of Atomic Energy for the first time in Eurasia. In August, 1949 the first Soviet atomic bomb was tested, and in August, 1953 a hydrogen (thermonuclear) bomb was tested in the USSR ahead of the United States.

Yet the age of nuclear power began only in 1954 when the first atomic power plant in the world was put into operation in Obninsk (USSR). About 200 nuclear reactors are currently in operation all over the world. By the year 2000, industrially developed countries plan to increase the generation of power by atomic plants so that it will account for 30 to 50% of all power available. By that time it is also anticipated that the first commercial thermonuclear power plants will be put into operation.

Between 1932 and 1956 antiparticles were discovered—positron (antielectron), antiproton, and antineutron—and that they were annihilated when they combined with ordinary matter, i.e. they disappeared with the release of the maximum amount of energy possible, i.e. $E = mc^2$, where m is the mass of particles, and c is the velocity of light. This energy amounts to some 25 million kWh per gram of particles. In 1965 (in the USA) and in 1971 (in the USSR) the first antiatoms were artificially obtained: antideuteron and antihelium-III respectively. The mysterious particle, neutrino, was exposed as a carrier of weak interactions. This particle has neither rest mass nor charge. It is continuously moving at a speed approaching the velocity of light and has an extremely high penetrating power. A neutrino can fly through 250 globes without reacting with any part of them.

Matter 'vanished' more than once during these stormy 100 years. The first 'thief' of matter was born that very year when Thomson gave his definition of energy. It was Wilhelm Ostwald (b. 1853, d. 1932), a German physicist, chemist, philosopher, artist, and musician. Already by his 50th year he had written 6000 pages of textbooks, reference and other books, 300 scientific papers, about 400 essays, and 900 reviews! He was brought up in Riga, in a family of German origin, graduated from the University of Dorpat (Tartu) where he received a doctorate in chemistry and a professorship. Between 1887 and

1906 he was a professor of the University of Leipzig and the Head of the Physico-Chemical Institute which he had founded. Having failed to obtain permission not to lecture, he resigned at 53 years of age and held no office from that time on. But his scientific work did not stop.... In 1909 he received the Nobel prize for a series of works in chemistry.

Ostwald was unlucky—he became a scientist when everybody's attention was focussed on energy and the structure of the atom was yet undiscovered. His vigorous temperament and passion for speculation made him the head of 'energetism', i.e. a semiphilosophical doctrine which called for the replacement of matter by energy, and an advocate of the principle of 'economy of thinking'. This principle implied the negation of atomism as excessive information: Why should we bother with the structure of the atom if all problems can be solved with the help of macroscopic dependences of thermodynamics? In "The Insolvency of Scientific Materialism and Ways of the Liquidation of the Latter" (!) he wrote: "Matter is nothing but a group of various forms of energy spatially and regularly interconnected." From this assumption he proceeded to treat only three forms of energy: linear (gravitation), surface (the tension of liquids), and volumetric (a change in volume). He used to begin his lectures with the topic "Energy and Its Conversions", and lived 25 years after retirement at his villa "Energy" in Grossbothen....

Ostwald proposed to "eliminate the opposition" of matter to spirit by reducing them to a third element (energy), which would have led to the concept of motion without matter. "But what then moves?" Lenin asked the advocates of energetism. If matter dissolves in energy and vanishes, motion must be a function of thought. But if "thought (idea, sensation, etc.) remains when matter vanishes, it means that you have surreptitiously passed over to the point of view of philosophical idealism". On the other hand, Lenin pointed out, the expressions 'matter vanishes', 'matter is reduced to electricity', and so forth, are gnoseologically helpless expressions of the idea that new forms of matter and material motion are discovered and old forms are reduced to new forms, and so forth.

After the discovery of the structure of the atom and other physical phenomena, the popularity of energetism fell rapidly. But after Einstein had established the relation of energy to mass as $E = mc^2$, a new wave of energetism was stirred. This was new energetism headed by the German physicist Werner Heisenberg (b. 1901, d. 1976), another Nobel laureate. "Three of the principal forms of energy," stated Heisenberg, "have a special stability. These are the electron, proton, and neutron. Matter ... consists of these forms of energy to which the energy of motion should always be added." In fact, the establishment of this dependence changed nothing in the material world. Different forms of matter and motion continued to convert into other forms as they had done before, but the idea of dynamic mass m_g was added to the notion of rest mass m_0 together with the concept of their interconversion, since $m = m_0 + m_g$. Thus the coalescence of material particles of electron and positron, having the aggregate mass Σm_0, brings about the formation of particles of electromagnetic field, that is photons having the aggregate mass Σm_g, but $\Sigma m_0 = \Sigma m_g$.

Thus there is no ready answer to the question: How many faces does the queen of the world have? There are also no recipes for how to determine them. Yet a Soviet physicist, K. A. Putilov, wrote in "Lectures on Thermodynamics" published in 1939: "...different sciences have different objectives and methods. Thus the forms of energy should be classified differently." He made a list of classifications for mechanics, thermodynamics, applied physics, and technological economics. But the classifications overlapped each other and termed the same forms of energy differently; there was no reason to regard them as comprehensive. This is natural because matter is the same for all sciences as well as *its forms, forms of motion, and stressed state—interaction.*

The experience in classifying material objects based on the works by Engels demonstrates that a complex approach should be employed to the classification of the forms of energy, which includes these three criteria because any one of them taken alone is insufficient. Indeed, the same forms of matter participate in various forms of motion (the electron, for example, may participate in electric, chemical, thermal, etc., motion). The forms of motion do not yet include stressed states. Which form of motion corresponds, for instance, to the potential energy of a suspended weight, which results from gravitational interaction? Yet the only four clearly defined classes of physical interaction, i.e. nuclear (strong), electromagnetic, 'neutrino' (weak), and gravitational (ultraweak), do not provide the bases for defining all variants of energy-producing phenomena. It is very tempting to compile a classification of the forms of energy (similar to Mendeleev's periodic table of elements) based on the stepped conversion of quantity into quality, for which purpose the formula $E = mc^2$ may be used. Indeed, thermonuclear reactions release 0.65% of all energy, nuclear fission reactions, 0.09%, chemical reactions, 5×10^{-9}%. But as we go further there are no distinct boundaries between the figures.

There is one more possibility which may seem easy at first glance. This is to classify the forms of energy on the basis of the convertibility of phenomena into a certain 'standard' form of energy, for example, mechanical. However, it is difficult to give a clear and comprehensive definition to the notion of 'conversion'. And how can one guarantee that all direct conversions are possible?

Thus we are left with a complex criterion: *forms of matter-forms of motion-forms of interaction.*

Let us agree that the energy of the free motion of a body or a particle will be called mechanical energy, and the energy of the chaotic motion and interaction of particles of material macrosystems will be called heat. Then the portion of heat, which may be liberated and converted into other forms of energy, given temperature differences, will be called thermal energy. The energy of all forms of ordered motion of electrons in macrobodies will be called electric energy, or electrodynamic energy, which is a rather unusual but more exact term. The particles of fields, such as mesons, photons, neutrinos, and gravitons, move continuously, which allows us to distinguish between the following forms of energy: 'meson' ('meson-dynamic'), 'photon' ('photon-dynamic'), or electromagnetic, 'neutrino-dynamic', and 'gravidynamic'.

If we consider 'stressed states' which result from the forces of interaction between bodies, we shall derive the potential forms of energy. The total energy of a matter-antimatter system, equal to the energy of rest and motion released during annihilation, may be called annihilation energy. Annihilation may result from a nuclear or electromagnetic (less likely) interaction. The binding energy of nucleons in the nucleus, which is released in the process of the fission of heavy nuclei and the synthesis of light nuclei, is called nuclear energy. The energy released in chemical reactions as a result of the rearrangement of the electron shells of molecules is called chemical energy. An electromagnetic interaction determines the potential energy of bodies in electric and magnetic fields, i.e. electrostatic and magnetic energy. Similarly, we must relate weak interactions to 'neutrino-static' energy, and ultraweak interactions to gravitational energy. If a steel spring or gas is compressed at constant temperature, it will result in the accumulation of energy which may be called elastic. This energy is caused by electromagnetic and gravitational interactions and thermal motion.

The resultant classification of the forms of energy covers all variants of energy conversions on Earth:

Thermal	Annihilation
Mechanical	Nuclear
Electric	Chemical
Electromagnetic	Electrostatic
Meson	Magnetic
Photon	Neutrino-static
Gravidynamic	Gravitational
Neutrino-dynamic	Elastic

The vibrational and inertial forms of energy are sometimes mentioned, but vibration and inertia are present in all forms of matter and motion and thus are covered by the above-mentioned forms of energy. Sound energy, for example, is a variety of mechanical energy. 'Biological energy' is frequently treated as a special form of energy. Yet biological processes are only a special group of physico-chemical processes involving the same forms of energy as others. Mayer and Helmholtz were already aware of this. The chemical energy of food normally converts into thermal, mechanical, electric, and sometimes into light (electromagnetic) energy. Thus it is preferable to speak about the biological transformers of energy rather than about biological energy.

These are the 'faces' of our multifaceted energy-queen. Is it possible to increase or decrease the number of them? Perhaps it is, but this requires new evidence.

The Distribution of Roles

Thus we know that the queen has sixteen faces so far. But what is the role of each form? Are the roles distributed accordingly? The performance is called "The Practical Activity of Man". The practical value of the above-listed forms of energy varies. They differ by the following factors:

—the availability and amount of resources on Earth;

—the capacity to renew these resources;

—the capacity to be used directly;

—the capacity to be accumulated and conserved;

—the capacity to be efficiently transmitted over considerable distances;

—the ability to efficiently convert into forms which are used in practice;

—the rate of conversion into other forms;

—its concentration;

—its orderliness, etc.

The great producer of this performance—Nature—reduces our choice of the sources of energy to a rather limited company of nonrenewable and regularly renewable resources.

From the continuously renewable resources of energy we make direct use only of the electromagnetic radiation of the Sun, a natural fusion* 'reactor'. The heat and radiant energy which it generates nourish the Earth's vegetation on which all animals and humans live. Only a negligible portion of the energy of rivers, wind, and heat from the Earth's interior serve us in their natural forms, that is they are not converted into the forms of energy we use, and which we shall call 'useful energies'.

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* It may be also a vacuum reactor since, as will be discussed below, there is an assumption that 'vacuum energy' exists in space.

There are only four such forms of energy. Some 75% of all the energy consumed is thermal energy, 24% is mechanical energy, and 1% is electric and light energy.

Natural Resources of Energy and Their Values (kWh)

Nonrenewable Resources (Total)	
Nuclear energy of fusion	$100{,}000{,}000 \times 10^{12}$
Nuclear energy of fission	$547{,}000 \times 10^{12}$
Chemical energy of organic fuels	$55{,}000 \times 10^{12}$
Internal heat of the Earth	134×10^{12}
Annually Renewable Resources	
Energy of the tides	$70{,}000 \times 10^{12}$
Energy of sunlight falling on Earth	$580{,}000 \times 10^{12}$
Energy of sunlight accumulated in the upper layers of the atmosphere (150 to 200 km) in the form of atomic oxygen and nitrogen	0.012×10^{12}
Energy of the wind	1700×10^{12}
Energy of the rivers	18×10^{12}

The demand for heat is to meet the needs of technology (smelting, drying, etc.) and domestic heating. Electricity is used, for example, to manufacture aluminum, but its principal task is the transmission of energy over long distance. The radiant energy of the short-wave spectrum is used for illumination.

Table 1 indicates that the demand for mechanical energy will grow relatively, and that for heat will decrease, but the *absolute consumption of both forms of energy will increase continuously proportional to the gross output of every country*, as was true in the past. The production of electric power will increase rapidly.

Thus we see that the nuclear, chemical, mechanical, thermal, and electromagnetic forms of energy function as resources, whereas the thermal, mechanical, electromagnetic, and electric forms of energy are useful forms. But what about the other ten forms of energy? The gravitational, electrostatic, magnetic, and elastic forms are used to accumulate energy, but the remaining six are like stage scenery, their significance is purely theoretical. The functions and roles are clear now. Let us follow the action of the performance.

The chemical energy of fossil fuels which are being barbarously wasted is the star, the most useful form of energy. Fossil fuels account for only a fraction of one per cent of all the energy available on Earth, but the rate at which it is being decreased is catastrophic. Chemical energy is practically nonrenewable because it takes thousands of years for fossil fuels to be accumulated, and forests have been destroyed more than cultivated in the last few centuries.

Table 1. **World Demand for Thermal and Mechanical Energy***

	1952**	1975	2000
Total (billion MkWh)	10.2	27	84
Heat (%)	80	70	66.5
Mechanical energy of power plants (%)	10	19	23
Mechanical energy of transportation vehicles (%)	10	11	10.5

* Including electric energy converted into these forms.
** Actual data; 1975 and 2000 figures are taken from a UN forecast, 1954.

When the first nuclear reactor was put into operation in December, 1942, fission and fusion fuels appeared as new sources of energy. Their wide application is being regarded as a cure for the power crisis and a way to conserve chemical resources for the next few centuries. Another way is to utilize the renewable sources of energy: solar radiation, tides, wind, geothermal heat, and rain flows. A third way is to economize on the power consumption by improving the technology of energy transformation. A fourth way is to accelerate the process of photosynthesis. A fifth way is to find new sources of energy as yet imagined.

Chemical energy has a number of advantages over the other forms: its fuels are easily transported, its concentration is very high, and it can be stored for a long time and easily converted into useful forms. For these reasons a great deal of research is being conducted to discover ways to convert the other forms of energy into chemical energy, for example, by decomposing water into hydrogen and oxygen by an electric current or by fusion technology. Hydrogen and oxygen will be used for transportation after the fossil fuels have been exhausted on Earth, and the near future will see the application of these gases in the environment protection because the reaction between them generates a harmless and useful product, i.e. water. But the highest power is contained in annihilation fuel: 1 g of matter and antimatter contains 25 million kWh of power. However, there is no antimatter in our part of the universe. Under laboratory conditions 1 kW of power is expended to generate 0.01 kW of annihilation power.

The Interconversion of Faces

A comprehensive analysis of power processes leads us to the conclusion that for the conversion of forms of energy at least two conditions must be met: (1) an adequate level of energy concentration must be secured and (2) a working medium having the necessary properties must be selected. A low concentration, for example, makes the conversion of heat released by flue gases into nuclear energy and fuel impossible. No matter how many times a dielectric crosses magnetic lines of force, it will not turn the mechanical energy of its motion into electric energy because a conductor is required.

The conversion of potential energies is even more complicated. Two pieces of uranium, the total mass of which is equal to the critical mass, will undergo a fission reaction if brought close together. But is there any way of turning these two pieces of uranium, which have a store of potential energy, into a liquid or gaseous fuel which, when mixed with oxygen, may be burned in an automobile engine and so release the nuclear potential? There is no way to do this. The only way is to introduce an intermediate stage during which the nuclear potential energy is converted into electromagnetic energy and then used to decompose water into hydrogen and oxygen, thereby generating a store of chemical energy. The heat of a nuclear reaction can be used to turn coal into 'gasoline'. The

Table 2. **Matrix of Possible and Expedient Conversions and Transformations of the Forms of Energy Which Have Practical Value**

	Form of energy	Role	1	2	3	4	5	6	7	8	9	10
1	Nuclear	NES & AES	◐	⊕	△+	+	⊕	⊕	+	⊕	●	⊕
2	Chemical	NES & AES; AE	−	◐	+	+	⊕	+	−	●	●	⊕
3	Electromagnetic	EC; NES	−	●	◐	+	+	−	−	◐	◐	+
4	Gravitational	NES	−	−	−	⊕	⊕	−	−	◐	+	◐
5	Elastic	AES; AE	−	−	−	⊕	+	+	+	+	+	◐
6	Electrostatic	AES; AE	−	−	−	+	+	+	+	+	+	+
7	Magnetic	AES; AE	−	−	−	+	+	+	+	+	+	⊕
8	Electric	EC	−	⊕	+	+	+	+	+	◐	△+	+
9	Thermal	NES & AES; AE	−	+	△+	−	⊕	−	−	+	●	●
10	Mechanical	NES & AES; AE	−	−	−	⊕	⊕	+	+	●	+	●

Symbols:

−	direct conversion is impossible
+	direct conversion is possible but has no practical value
△+	direct conversion is possible and has practical value but not for power engineering
⊕	direct conversion is possible, has practical value but is not used yet
◐	the same as above but partially used
●	the same as above but widely used

NES natural energy source
AES artificial energy source
AE accumulator of energy
EC energy carrier

system which carries the potential energy seems to be closed, and if opened it would convert only kinetic energies. Thus we pretend that the 'kinetic stage' does not exist, since it is an intermediary in this operation and does not require, in the majority of cases, any special device.

Having decided not to consider the forms of energy which have no practical value, we proceed now to an analysis of the possible conversions of the remaining forms with the help of the matrix given in Table 2.

Strictly speaking, all conversions of energy should also involve a change in the gravitational energy of its carrier-systems if their position in relation to the Earth's surface alters.

This matrix of energy conversions gives us food for thought. Firstly, the possibilities are limited and all the more so if we consider that other variants are hard to imagine. Secondly, the major, simplest, safest, and most advantageous methods have been tried already, and further improvement may only increase the efficiency of the conversions and the specific power productivity, i.e. the power of a transformer. There seems to remain some scope for improvement in the direct conversion of nuclear energy into electric and mechanical energy, chemical energy into mechanical, and gravitational energy into mechanical. The conversion of nuclear energy into chemical and elastic energy, and that of gravitational energy into elastic, e.g. by compressing springs and gas cylinders on the bottom of the sea, are also promising.

A 'Shagreen Leather' for Humanity

The hero of Balzac's novel *Shagreen Leather* could have all his wishes magically fulfilled, but each wish decreased his talisman—a piece of shagreen leather. The piece seemed large enough to last for several human lives, but the more his wishes were fulfilled, the more new ones he could imagine.... The man died in the middle of his life....

But isn't energy a 'shagreen leather' for humanity? Everything on Earth—food, dwellings, clothes, cars, airplanes, TV sets, and so forth—must be paid for with one and only one currency. This is energy, the stores of which are rapidly diminishing.

We have designated ten forms of energy which currently have practical value. Our next objective is to consider the material systems that are sources (carriers) of these forms of energy and to determine the composition of a 'shagreen leather' for humanity. The size of the 'leather' is determined by the numerical values of the resources of energy.

Mechanical energy is supplied by various systems, the motion of which is either natural or artificial. These systems include the motion of water in rivers, tides and ebbs currents, storms, wind, and flywheels. Flywheels may store up to 200 kJ/kg, the limit being fixed by the ultimate tensile strength of steel.

Gravitational energy is generated by devices changing fheir weight which alters their altitude above the surface ot the Earth or the depth under water. These are the aerostats, or lighter-than-air aircraft, and hydrostats, or submersible craft. The total amount of gravitational energy per kilogram of a body's mass is about 62,400 kJ/kg on the Earth's surface (this is the amount of work required to launch a body with a mass equal to 1 kg into space). Atmospheric pressure may sometimes launch a rocket from a tube, from which air has been pumped, faster than a missile can be launched with a solid fuel. The water pressure at great depths can be employed to launch a projectile or to take soil samples from the bottom of the sea.

Elastic energy is generated by springs and compressed gases. The power capacity of steel springs reaches 0.2 kJ/kg and that of rubber springs is 0.35 kJ/kg. The figures are low, but this deficiency is compensated for by the simplicity of the design (the same device is simultaneously a source and a converter of energy), the absence of any reaction products, and the renewability of the energy source. New polymer materials will increase the power capacity of springs by many times. If the original pressure is equal to 1010 bars and the final pressure is 10 bars, a compressed gas accumulates about 100 kJ/l as compared with 600 kJ/l accumulated by a mixture of kerosene and air compressed to 200 bars. A mixture of kerosene and atmospheric air gives (consumption not counted) 35,000 kJ/l of kerosene.

Natural sources of thermal energy include solar radiation, and the temperature differences between the surface and deeper layers of land and sea (up to 10-20°). Heat can be accumulated artificially with the help of melted metals and superheated liquids. It is possible to accumulate 'negative heat' by creating liquid air, hydrogen, or oxygen.

Electromagnetic energy is continuously delivered to Earth from the Sun at the rate of 3000 $kJ/m^2 \cdot h$. The solar photon 'wind' could propel a vessel in space if it is equipped with a special 'sail'. The pressure of this 'wind' on the Earth's surface is only 500 Pa and has no practical value.

Electrostatic energy can be accumulated by capacitors (modified 'Leyden jars'). Capacitors may accumulate up to 440 kJ/l but it is hard to discharge them slowly. The power capacity of electrets (electric analogues of permanent magnets) is still lower.

Magnetostatic energy is contained in permanent magnets which are manufactured artificially. The power capacity and power of these magnets are low. Electromagnets operate only if electric current is continuously supplied and so they cannot accumulate energy.

There are no *natural sources of electric energy* other than lightning. The artificial sources include capacitors and batteries.

Chemical energy is contained in two-component fuels consisting of a combustible and an oxidizer. The best combustible is hydrogen; its power capacity is 120,000 kJ/kg; the power capacity per kilogram of a mixture of hydrogen and oxygen (in the ratio of one to three required for its complete combustion) is 13,300 kJ/kg. However, pure hydrogen does not exist in nature; it is obtained by decomposing water. It is more convenient to use liquid hydrogen (because of its small volume), but this requires extremely low temperatures.

There are considerable deposits of fossil organic fuels in nature. These include oil, natural gas, coal, and shales. Their power capacity varies from 20,000 to 40,000 kJ/kg of fuel. One kilogram of a completely combustible mixture of fuel and air has a power capacity of 2500 kJ (this figure is valid for almost all fuels). Sometimes inorganic fuels are used (the current application is limited to rockets). These include silicon, magnesium, aluminum, boron, lithium, etc. These fuels are expensive and inconvenient to use (the fuel must be solid and solid products of combustion are formed).

Finally, *nuclear energy* is contained in nuclear fuels. Fission using thermal neutrons is only possible with uranium-235, the content of which in natural uranium is a mere 0.712%, the rest being uranium-238. The latter captures thermal neutrons, thereby making a chain reaction possible only in very large reactors. Thus natural uranium is enriched between 2 and 20% with uranium-235. A two-step process which produces a new nuclear fuel, i.e. plutonium-239 and uranium-233, permits the use of uranium-238 and thorium-232 but only by fast-neutron fission. This will enhance the efficiency of the use of uranium, with regard to wastes, by twenty to thirty times and doubles the resources of nuclear fission fuel. These breeder-reactors are smaller in size and weight, and they seem to have a great future. And that is all.

Radioactive isotopes are still expensive; they generate a negligible amount of energy, but for a very long period of time (30 years or more), continuously, and steadily. These isotopes include cobalt-60, strontium-90, and cesium-137; they emit alpha rays (helium nuclei), beta rays (electrons), and gamma rays (photons).

The power capacity of nuclear fuels is very high; that of uranium-235, for example, is 6.7×10^{10} kJ/kg. The power capacity of thermonuclear fuels is seven to ten times higher. Thermonuclear fuels are the nuclei of the lightest elements such as the isotopes of hydrogen (tritium and deuterium) which combine to release at a temperature of several tens of millions of degrees! In bombs this temperature is created by the explosion of a nuclear fission device. Over the last twenty years numerous attempts have been made to induce a controlled thermonuclear reaction, but without any notable success. Yet specialists are optimistic about this goal. The amount of deuterium contained per liter of sea water is equivalent to 160-200 l of kerosene.

From a Splinter to a Reactor and Further...

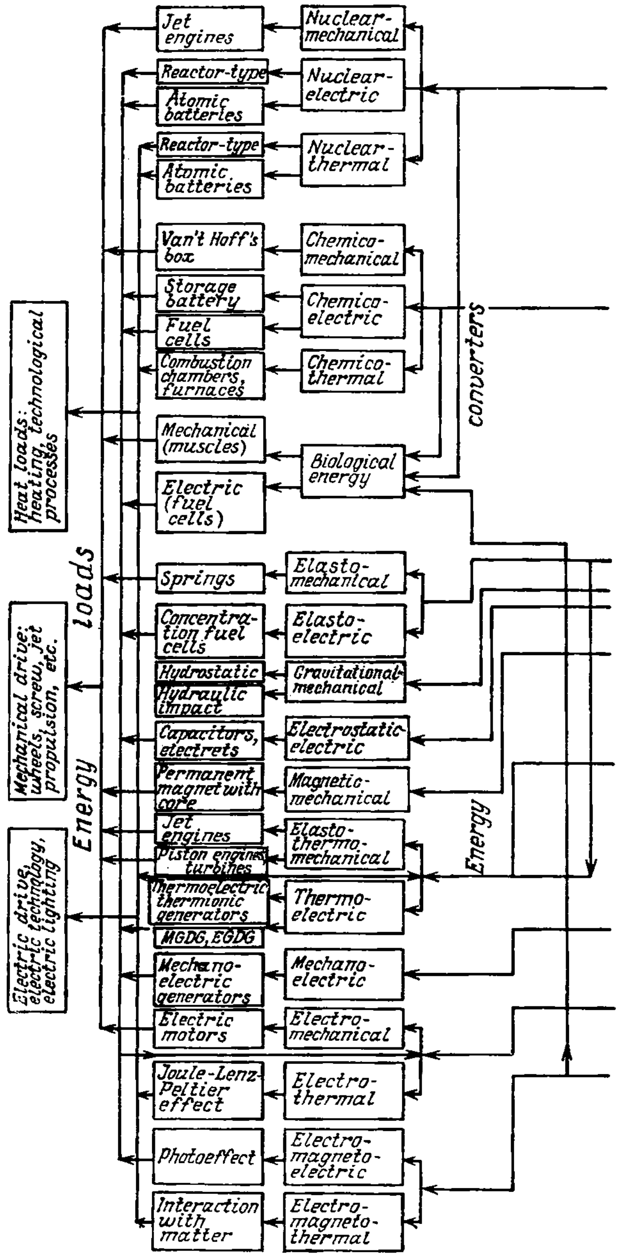
Our search for understanding has led us to the ordinary technology which supplies us with energy, i.e. to energy converters and power plants. If the number of steps in converting the forms of energy is considered, we would be surprised by the fact that a sophisticated device such as a nuclear reactor is not very far from the stick and log in the hands of primitive man. Both devices belong to the same class of heat generators. Now that we know all sources of energy and its directly used forms (it is sufficient to consider thermal, mechanical, and electric energy, because the fraction of luminous energy is insignificant and this energy is usually generated by electric power), we may draw a flow diagram which demonstrates all the possible combinations, i.e. all the possible types of energy converters (EC) and power plants (PP). If we exclude the unreal combinations, we shall get a clear idea of the existing and probable EC's and PP's.

Complex criteria are required to estimate the efficiency of each type. The values of these criteria would reveal the potential capabilities of and prospects for the various energy converters and power plants. However, this general task is complicated because the criteria should take into account the power capacity of the mass of a given energy source and the degree to which it is utilized, the efficiency of the energy converter, its specific power (by weight and by volume), its independence in operation, controllability, safety, convenience of operation, sophistication, etc. Complex criteria cannot be calculated by multiplying numerical values of the listed factors, since their scale, the control range of the numerical values, and respective roles are different. Thus we must either do the gigantic work of analyzing the significance, i.e. specific 'weight', of each factor in the general criteria and invent an appropriate scale to measure it or forecast it by each factor taken separately. The composition of the criteria and their relative 'weights' may vary depending on the application and purpose (military or civilian equipment, transportation vehicles or stationary plants, etc.). The flow diagram demonstrates that the variety of energy converters and power plants is not great. The majority of them are commercially available: steam turbines with electric generators (power plants), gas turbines and jet engines (aviation), internal combustion piston engines (automobiles). All these may be mounted on ships, locomotives, and other vehicles and equipment.

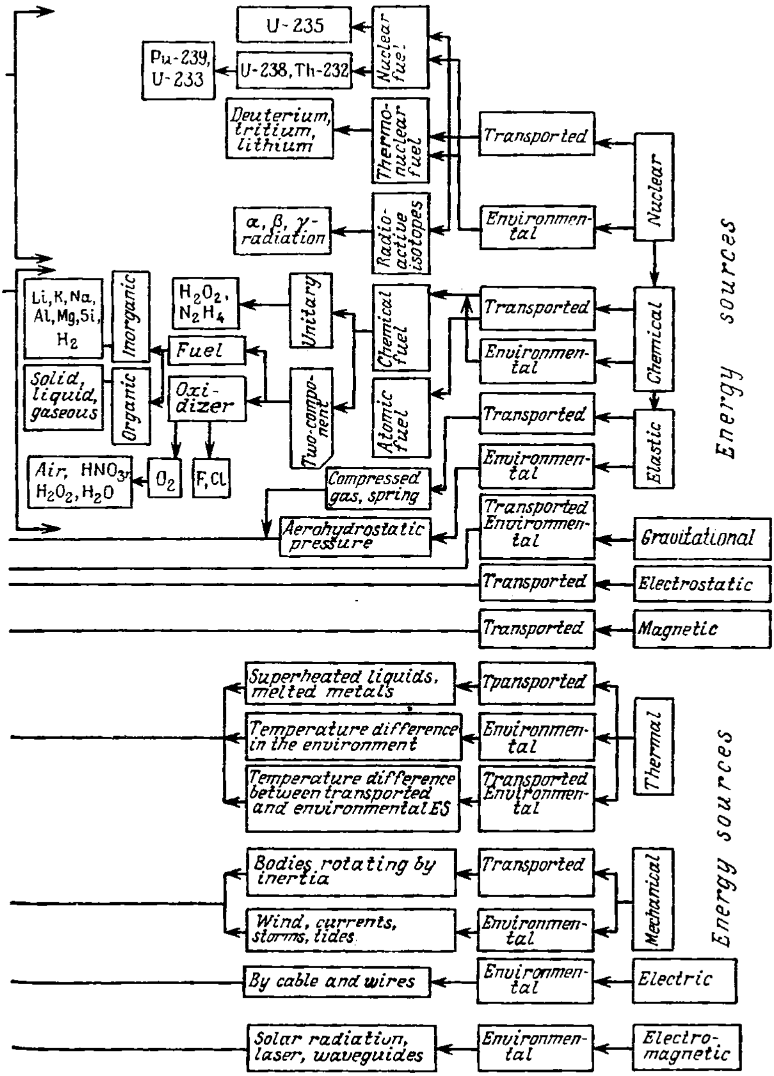
Atomic power plants, each consisting of a heat-generating reactor and steam turbine, began to be built between 1952 and 1954. The development of energy converters capable of generating electricity started between 1958 and 1960. These include fuel cells (FC), thermoelectric generators (TEG), thermionic generators (TIG), magneto gas-dynamic and electro gas-dynamic generators (MGDG and EGDG), solar batteries (SB), and atomic electric batteries.

Fuel cells operate like automobile batteries, i.e. by 'cold combustion', the oxidation of the fuel (hydrogen, for example) by atmospheric oxygen directly generating electric current instead of heat. The operation of semiconductor thermoelectric generators is based on the Seebeck effect. Thermionic generators operate according to the same principle but their electrodes are separated and electrons flow between them owing to thermal emission, i.e. emission of electrons from a heated cathode surface. D. Arago was aware of the principle of a magneto gas-dynamic generator: if a magnetic field is crossed by a flow of an electrically conducting gas, an electric current occurs in the gas perpendicular to the field and direction of the flow. Magneto gas-dynamic generators have high power but low efficiency, because temperatures between 2000 and 3000 °C are required for the gas to conduct. If the heat from the gas which has been produced in a magneto gas-dynamic generator is fed to a steam turbine, the combined efficiency (see below) of this power plant would reach 50-55%, but the working capacity of the gas within the temperature range from 550 to 2000 °C (the maximum temperature of the steam turbine's cycle) is not utilized. Currently available materials cannot endure the working temperature of a magneto gas-dynamic generator for a long time. The device requires a cooling system and creates other technical problems....

Flow Diagram of energy Sources, Conver
(read the diagram



ters, and Loads (Power Plants)
from right to left)



Solar batteries are based on photoeffect: the 'knocking-out' of electrons from atoms of germanium and silicon by photons of the sunlight. These electrons generate an electric current when the circuit is closed. Atomic batteries transform the radiant energy of radioactive isotopes into electric current. The efficiency of military equipment is estimated by the weapon's destructive power; that of civilian devices is assessed by their operational efficiency and power. The operational efficiency of power plants is measured by the output, or consumption of power per unit of generated energy. Efficiency is the ratio of the output of useful energy of a machine or other energy-converting plant to the input energy. This dimensionless quantity is less than unity, but it is usually expressed as a percentage. Specific consumption is inversely proportional to efficiency.

The efficiency of nonthermal generators, in which losses result only from the irreversibility of the actual processes, i.e. mainly from friction, heat exchange with the environment, etc., approaches 100%. The efficiency of generators with a thermal stage of conversion, expressed by $\eta_{th} = 1 - q_2/q_1$, is always lower than 100% because a lot of heat, q_2, is transferred to the cold source. It also depends upon the difference between the maximum and minimum temperatures, which is expressed by the Carnot efficiency, i.e. $\eta_C = 1 - T_2/T_1$.

The efficiency, for example, of a primary energy converter is 60 to 80% (fuel cells), 35 to 40% (internal combustion piston engines), 35 to 40% (steam turbines), 25 to 35% (gas turbines). The efficiency of a steam engine (no longer manufactured) was a mere 5 to 8%. The efficiency of a secondary energy converter, for example, an electric motor or an electric generator, reaches 95 to 98%. The efficiency of a thermoelectric generator or a thermionic generator or that of a solar battery is about 10 to 15%. The efficiency of a magneto gas-dynamic power plant is $\eta_{MGDP} = \eta_{MGDG} + \eta_{ICPP}(1 - \eta_{MGDG}) \cong 0.20 + 0.40(1 - 0.20) = 0.52$, or 52%.

Sometimes fuel components may be partially taken from the environment (oxygen, for example, while a ship is in motion, or solar energy). This power is 'free' and it is better in this case to estimate the efficiency with the help of an energy utilization factor (EUF) which is the ratio of all the generated useful energy (work) to the amount of expended energy which was transported. Obviously the EUF, in contrast to efficiency, may be much higher than 100%. In some fuel cells, a reaction is accompanied by an increase in the number of moles of gas (for example, $2C + O_2 = 2CO$). If the cell is cooled, these reactions convert not only the heat of the reaction into electric power but also the energy of the 'free' heat which comes from the environment. This is so far the only way to utilize environmental heat in power engineering, and further research is now under way. If the electric energy generated by such a cell were only related to the energy of the reaction, this would 'violate' the principle of conservation of energy, since the 'efficiency' (it would be an EUF in fact) would exceed 100%. But if the consumption of heat which comes from the environment were considered, the result would be ordinary because the EUF would become an efficiency and would not exceed 100%.

The specific power of a generator, i.e. $P = F \cdot \omega$, the power per unit mass or volume, is proportional to the applied force F (for example, the force of the pressure of gas) and the flow of the working medium (gas, steam, plasma) or the velocity of motion of the working element (piston, turbine wheel, etc.), ω. Possibilities for increasing force are limited. Thus pressures seldom exceed 100 atmospheres, and velocities may only exceed the velocity of sound by two or three times. The velocity of a piston's motion inside a cylinder, for example, never exceeds 20 m/s, that of the rotation of turbine blades reaches 3000 m/s, and jet aircraft fly at even higher speeds. It is thus not surprising that the power of a spacecraft may exceed 20 million horsepower.

The working process of generators may be either stationary or pulsatory. A stationary process is a characteristic of turbines and jet engines and occurs under the constant pressure of a combustion chamber. A pulsatory process takes place in piston engines, turbines, and jet engines in which the combustion chamber is closed off by valves. The operation of a percussion fuse is also based on pulses—shock waves—which create the high gas temperatures and ionization. Thus, a slow compression of air up to a pressure of 1000 bars without a heat exchange with the environment results in a temperature of 1500 °C, while a shock-wave compression to the same pressure yields 13,700 °C. Pulsatory processes can supply energy to start energy-release reactions, decrease the thermal stress of structures, and so forth. Magnetic pistons and 'plugs' function as pistons and valves controlling the pulsatory processes in electron-ion converters.

Generators of mechanical energy (engines) have another feature. This is the mode of motion of the given vehicle (automobile, airplane, etc.), which may be either action- or reaction-type motion. The first mode (wheels, for example) is more efficient at low speeds, when its efficiency reaches 70 to 80%, compared to the 0.5 to 3% efficiencies of reaction drive at these speeds. The second mode (jets, for example) is better at high speeds when their efficiency reaches 70%.

Predicting the increases in the efficiencies of power plants must be done with care. We cannot be overoptimistic about temperatures higher than $T_1 = 2000$ K At this temperature (and that of the environment $T_2 \approx$ 300 K, $t_2 = 27$ °C), the Carnot efficiency reaches 85%. If the temperature goes up to 3000 K, the efficiency is still lower than 90%. The inexpensive materials currently available can only endure temperatures up to 1300 K. As the temperature increases, more heat is liberated into the environment and thus greater temperatures are needed to provide for the reliability and durability of the equipment. Fuel cells are promising in minor power engineering and transportation.

Various biological energy converters, the study of which has begun recently, are also of interest. All converters of the energy of renewable resources—especially that of solar radiation—must be improved.

Chemical energy can also be directly converted into mechanical energy using 'Van't Hoff's box', a vessel in which the volume increase that accompanies a reaction with gaseous products, at constant temperature, pushes a piston which performs mechanical work. This is achieved by separating reagents and reaction products by semipermeable membranes which control the direction of the reaction. However, membranes have not yet been designed for reasonable reagents.

The development of 'machineless' energy converters (tools for the manufacturing industry) is now receiving great attention. Chemical reactions, plasma jets, and lasers now replace lathes and drills.

Concentration, Transformation, Accumulation

These processes are often combined in one device along with a fourth one, i.e. the 'conversion of energy'. Charging a battery is, in fact, the conversion of electric energy into chemical energy. It is also the accumulation of energy, the concentration of which may increase and the potential of which may alter, i.e. a 'transformation' may occur. But in general the term 'transformers' is also used for those devices which alter the voltage of an electric current.

However, there are other ways of concentrating energy. The work expended to operate a compressor, for example, produces a compressed gas. The higher the pressure of the gas, the higher the concentration of elastic energy. When we wind up a clock or pull a bowstring, we also increase the concentration of the elastic energy. The concentration of thermal energy in the products of combustion in a gas turbine is lowered from 2200 to 700 °C by feeding two or three times more air than required for complete combustion. The temperature is reduced to prevent the turbine blades from burning. Heating air with a stove is also a way of increasing the concentration of heat. This is clear.

But how can the concentration of heat be increased without heating? Heat pumps have been invented to perform the function of a 'thermocompressor'. These transform heat, by consuming a certain form of energy, from a low temperature level to a higher level. The most striking effect of this process is that four to six times more heat is obtained than is consumed (with an electric stove, the ratio is one to one).

A refrigerator is one such heat pump. Heat from the refrigerated cabinet is continuously 'pumped' into the environment as a result of the work performed by the electric motor to turn the compressor. Thus the 'trick question' as to whether a room can be cooled by leaving a refrigerator door open. The answer is 'no' because the room will be heated.

The design of a heat pump is very simple. It is a closed loop within which a material with a low boiling point (often ammonia or freon) circulates. The loop contains a compressor, a flash tank (this may be a throttle (a tube with a constrictor which strongly cools the gas passing through it) and two tubular heat exchangers (an evaporator and a radiator). The compressor compresses the vapor coming from the evaporator at the temperature of 2 °C to the pressure corresponding to the temperature of 67 °C and feeds it into the radiator. From this unit heat is released into the environment (a room, for example), after which a coolant (at the temperature of about 20 °C) is fed into the flash tank (restrictor) where it is cooled to a semiliquid state. Then the coolant proceeds to the evaporator in which it is evaporated by taking heat either from the refrigerated cabinet (in case of a refrigerator) or from the water, soil, or atmospheric air (in case of a thermocompressor). The cycle is then repeated. If the loop is installed in an apartment and equipped with a switch, it may be used to cool the apartment in summer and heat it in winter. Such a device is called an air conditioner. The maximum coefficient of utilization of heat in a thermocompressor, i.e. the Carnot efficiency, is $\xi_{th} = T_1 (T_1 - T_2) = 340/(340 - 275) = 5.2$. The real figure is naturally lower, although it reaches three or four.

These plants are best where fossil fuels are scarce but inexpensive electric power is available, and for railways and aviation. Heat pumps can heat or cool rooms without any of the pollution caused by the by-products of combustion.

There are also absorption, electric, and chemical heat pumps'. Electrical compressors are especially interesting. They are based on the Peltier effect. If an electric current passes through a closed circuit consisting of two dissimilar conductors, one of the junctions is heated and the other is cooled. Thus, if we place the junction in a room or cabinet, the area will be either heated or cooled.

A mechanism for changing the concentration of other forms of energy is even simpler. Mechanical energy, for example, can be transformed with 'transmissions', e.g. gear trains or belt transmissions.

The concentration, transformation, and accumulation of energy during photosynthesis is very interesting, and its importance for this planet cannot be overestimated. Chlorophyll, the green pigment of plants, concentrates and accumulates the low-potential luminous energy of the Sun, which is then converted into the chemical energy of vegetation (organic compounds synthesized from carbon dioxide and water). The whole world 'rests' upon this process. Photosynthesis not only increases the concentration of energy but also regulates the structure of matter. The irregular stable state, i.e. individual molecules of carbon dioxide and water, is changed by photosynthesis, by a regular, and thus less stable, state of large organic molecules.

In conclusion we may give some figures which 'speak for themselves'. The process of photosynthesis is called 'endergonic' because it increases the free energy of plants. Photosynthesis produces annually about 3×10^{11} tons of organic carbon, the chemical energy of which is 100 times more than that of the coal extracted in the same time interval, and 10,000 times more than the energy of moving water in the world.

Energy accumulation is an aspect of every energy using activity. Energy must be accumulated to induce a fusion reaction, to keep a car going downhill, to conserve power at a conventional power station at night when the demand is low, to use the power of wind and solar power plants, and so forth.

"Equations of the Motion of Energy in Bodies"

"...Never in my life have I read such sheer nonsense!" wrote K. I. Korostelev, professor of the University of Novorossiisk in a letter to a Petersburg academician, I. I. Somov. The professor's vituperation was directed at a doctoral thesis written by 28-year-old Nikolai Alekseevich Umov (b. 1846, d. 1915). The thesis was titled

"Equations of the Motion of Energy in Bodies", and Korostelev s opinion was shared by many. Nevertheless, the thesis was defended on the 27th of September, 1874 before the Council of the Department of Physics and Mathematics at Moscow University (after a 6-hour discussion).... Korostelev, however, preceded this remark by the admission: "I understand nothing of Umov's reasoning. I see therein a set of senseless formulas which prove nothing and result in nothing...."

Even a prominent physicist, A. G. Stoletov, wrote in the review coauthored by Professor Sludsky (both were the official opponents): "Mr. Umov's thesis 'Equations of the Motion of Energy in Bodies' is purely speculative.... The author finds it necessary (Chapter 1) to introduce generalized notions of the motion of energy into theoretical physics ... and to do this now when heat is at last considered motion, and the expression 'thermal current' has become relative and suggests a further mechanical analysis. This very relative and vague notion is generalized by Mr. Umov who applies it to all physical energy.... To justify himself, Mr. Umov recognizes the similarity between the principle of conservation of energy and the principle of conservation of matter (see page 2). But the idea of the motion of energy is in no way explained or justified by this similarity...," and so on.

Umov was so depressed by the resistance he met and the complete misunderstanding of his work that he never returned to this subject. This was, however, a mistake because the comments we cited all stem from psychological inertia which may be a flaw of even talented scientists. The dist nguished physicist Max Planck wrote bitterly in his autobiography: "The difficult part of my scientific life was that I rarely, practically never, got complete recognition of my new hypothesis which though sound I could only prove strictly theoretically." Planck concluded that new scientific ideas win not when opponents are persuaded to recognize their error but mainly when the opponents are dead, and the new generation assimilates the idea from the very start!

In his work, Umov translated general talks about short-range interaction into a language of concrete notions and functions. He formulated ideas about the localization of energy, its motion in space, the velocity of the motion, and many other notions. They seemed so unusual and even 'heretical' in his time that no one either in Russia or abroad gave them the credit they deserved. In the first section of his work, Umov introduced fundamental notions including that of energy flux, and derived a mathematical expression for the conservation of energy in its differential and integral forms. In the second and third sections he investigated the principles of the motion of energy in elastic bodies, in liquid media, and in the energy transfer between interacting bodies separated by space. For all cases he formulated mathematical components of the vector of energy density: the equations of the motion of energy.

Umov was still feeling the effect of his struggle over his thesis when a Croatian electrician and inventor, Nikola Tesla (b. 1856, d. 1943), started experimenting with wireless transmission. He finally succeeded in constructing (in 1899) a large radio station in Colorado, USA. The power of the station reached 200 kW, and energy was transmitted a distance of 1000 km. Yet this energy could light electric lamps and drive small electric motors only from the distance of 25 km or less. Thus the idea of energy transmission through the air was 'blowing in the wind', despite Stoletov's pessimism. Eleven years after Umov's work an English physicist, John Poynting (b. 1852, d. 1914), published a thesis on energy transfer in an electromagnetic field, after which energy transfer was unjustly associated with his name. Even the vector of the density of energy flux, which had first been introduced by Umov, was called the Poynting vector. Presently this vector is called the Umov-Poynting vector.

This was the theory, but what happens in practice, in real life? Energy is transferred in a fuel, by compressed springs or gases, by the weights falling down cords or liquids being transferred from one level to another, by capacitors, inductive coils, flywheels, metal melts at high temperatures, superheated liquids, and so forth The energy of fields is transferred by flows of their quanta: pi-mesons, photons, and gravitons.

However, technology and economics guide industry in its choice of the means for transferring energy. Thus in the recent past, electric power could be transmitted over power lines up to 1000 to 1200 km at a voltage of 400 kV. The voltage of modern lines reaches 750 kV, and 1250-kV ac-lines are under construction (this is the maximum value so far because of the losses due to coronal discharge, which may reach 100,000 kWh per one kilometer of line). The voltage of dc-lines may reach 1500 kV, and in the future, lines at 2000 to 2500 kV will be put into service. This will increase the power and distance of transmission by several times, which is of special importance for hydroelectric power engineering. Currently manufactured cables do not exceed 100 to 200 km in length.

When using thermal power stations, it is better to transport the coal, oil, or gas to the station rather than transmit the generated electric power long distances. For instance, the cost of transmitting 150 MW a distance of 400 km is equal to half the construction costs for a thermal power station with that capacity. It is even better to locate the power stations in the vicinity of the coal deposits and then build the industrial enterprises and economic regions around them. These tasks are solved with regard to the utilization factor of various forms of energy. The factor for electric power approaches 100%, that for the chemical energy of coal is 55% in industry, 40% in homes, and 4% in transportation. The figures for oil are approximately 20% higher than the first two figures and five or six times higher than the third (transportation); the utilization factor for solar radiation is 12%*, and so forth.

The exotic technologies of electromagnetic power transmission by waveguides (passing them through tubes), power transmission to vehicles by induction, and so on, can still be improved.

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* Since solar radiation is 'free', its utilization factor loses its conventional meaning.

The Queen's Formidable Shadow

Oh Spring, please do not leave us,
Wait a moment, be so kind!
...But already the bloom of leaves
Welcomes summer in its right...
I would greet the lovely comfort
Of green trees and summer nights,
But the autumn wind will come to
Tear down leaves—thus nature fights...
Fruits are ripe in early fall...
Take them, do not waste your time,
If you miss the crop will fall,
If they rot it is your crime,
And the rains will wash away
All the glamor, so nature dies.
It is impossible, they say,
To bathe in one river twice!

J. W. Goethe

Shadows Start Growing at Noon

In 1885 a professor at the University of Bonn, R. Clausius, published a treatise "On the Stores of Energy in Nature and the Utilization of Them to Our Benefit" in which he wrote:

"We extract as much coal from the Earth's depths as may be extracted with the help of available technology. But the number of railways, steamers, and industrial enterprises that consume coal is growing terribly fast. Thus it is inevitable to ask what humanity will do when all the coal is exhausted. This crisis is not a remote prospect, it may come in a short time."

Thus the shadow of the Queen of the World had started her march across the Earth at that very moment when science and technology were reaching their climax in the 19th century.

But to return to the time when the principle of conservation of energy was established, let us trace the course of events which led to the scientific explanation of this new phenomenon and formation of the notion of entropy. In 1849 W. Thomson found and studied the almost-forgotten memoirs of S. Carnot and delivered a "Report on Carnot's Theory" in which he treated this theory in the light of the new mechanical theory of heat. Having pointed out Carnot's erroneous assumption that heat is redistributed and not consumed in machines, he supported Carnot's conclusion about the conditions for conversion of heat into work: the presence of at least two sources of heat of different temperatures.

Less than a year passed after Thomson's "Report" when Clausius, a 28-year-old assistant professor of an artillery school and a graduate of the University of Berlin, published a paper called "On the Motive Power of Heat." He also treated S. Carnot's work from the position of the mechanical theory of heat and demonstrated, as Thomson had done, the correctness of Carnot's fundamental ideas. However, he reformulated the ideas into two laws. The first was that an amount of heat proportional to the work is consumed whenever heat performs work, and the second was that heat cannot move by itself from a cold body to a hot body. According to Clausius, the second law conforms to the Carnot principle which states that work is performed only when heat moves from a hot body to a cold body. To his credit, Clausius had the tact and scientific integrity not to underrate Carnot's contribution, although he had replaced the redistribution of heat in the first law by consumption, the two notions having quite different meanings.

In the same paper Clausius employed the second law to prove Carnot's theorem, i.e. the efficiency of the cycle does not depend upon the working medium, and formulated the Carnot function $C = 1/T$ for the first time. He also derived the famous equation for the efficiency of an ideal Carnot cycle, viz. $\eta_C = (T_1 - T_2)/T_1$.

Thus a new branch of science—thermodynamics—was founded. Thermodynamics is the theory that deals with the motion of heat, *thermē* meaning 'heat' in Greek and *dynamis* meaning 'power'.

That same year a 30-year-old graduate of the University of Edinburgh, William Rankine (b. 1820, d. 1872) (he became the Professor of Mechanics and Civil Engineering at the University of Glasgow in 1855), published a treatise on the thermodynamics of gases and steam. In 1857 he published a book on steam engines which was reprinted fourteen times before 1897! Like Clausius, Rankine proved that only a part of the heat generated by the heater goes to the cooling tank; another part that is proportional to the work performed 'vanishes'.

Scientists were only beginning to study Clausius and Rankine when W. Thomson published (in 1851) three papers under the common title "On the Dynamic Theory of Heat". He was elected to the Royal Society in the same year, having occupied the Physics Chair at the University of Glasgow for five years. He entered this university when he was ten years old. After graduating he began working for a professorship at Cambridge, and worked for a year in a laboratory in Paris. Having returned to Glasgow, he stayed there until the end of his life, and was eventually awarded a peerage, choosing the name Kelvin (after a small river flowing near the university) for his services to science.

Thomson treated the convertibility of various forms of energy into other forms (quantitatively) and derived another formulation of the second law (the Carnot-Clausius principle). This formulation stated that it is impossible to obtain mechanical action from anything by cooling it to a temperature lower than that of the surroundings with the help of an inanimate body.

Then Clapeyron, who persisted in supporting the theory of thermogen, proposed his own formulation of the second law, viz. a loss of animate force occurs each time two bodies of different temperatures come into contact, and heat flows directly from one body to the other. Similar ideas were expressed by other scientists.

In 1852 Thomson published a treatise "On the General Tendency of Degradation of Mechanical Energy in Nature" in which he divided all processes into reversible and irreversible ones. All real processes are irreversible. He pointed out that only systems in which reversible processes take place can have their 'mechanical energy' restored, i.e. their capacity to perform the same mechanical work. Irreversible processes, such as friction, heat conduction, and so on, impede the return of the system to its original state because their 'mechanical energy', i.e. their capacity to perform work, is decreased, and the 'mechanical energy degrades' by being converted into heat. Hence Thomson came to a momentous conclusion: "In the past, which is separated by a finite time interval from the present, the Earth was, and after finite time interval it will be again, in a state unfit for human life if only measures were taken in the past and will not be taken in the future which cannot be realized in the face of laws regulating the known processes which currently take place in the material world." This was a first hint at the concept of a 'heat death' but so far it applied only to the Earth....

In 1854 Clausius published a paper "On the Altered Form of the Second Element" in which he gave mathematical expressions to two laws for reversible, i.e. ideal, processes which do not exist in nature and occur infinitely slowly in a state of equilibrium of the system without the degradation of energy. A more exact differential form of these expressions looks like this. The first law, i.e. $dQ = dU + dA$, is the infinitesimal amount of heat fed into the system (e.g. the gas above the piston of an automobile engine) and should equal the infinitesimal change in the system's internal energy (dU) and infinitesimal amount of the work performed (dA). The second law, i.e. $\oint dQ/T$ (the sum of all 'conversions' dQ/T in reversible circular closed processes, that is cycles of heat engines), should equal zero. Thus an automobile engine's cycle consists of four processes: (1) compression of the working medium (gas) in the cylinder; (2) heat supply (combustion); (3) expansion (working stroke); (4) heat removal.

The same year, Rankine ('treading on Clausius' heels') formulated a slightly different expression of the second law. He treated the quantity dQ/T, which is similar to energy, as a 'function of the state of the system'. The latter expression means that any change in the system during the process does not depend on the nature of the process but only depends on the values of dQ/T at the beginning and at the end of the process. Rankine termed this quantity a 'thermodynamic function'.

After this, relative peace came to the 'heat front'. For eight years Clausius dared not publish the results of his application of the second law to real, irreversible processes. The reason was that he believed the results would lead to a conclusion which "deviates from conventional ideas".... Nevertheless, his evidence was published between 1862 and 1865. The second law was expressed as $dS \geqslant dQ/T$ (the equality sign stands for reversible processes and the sign 'is greater than' stands for irreversible processes. The quantity S was termed 'entropy'. The growth of S in irreversible processes characterizes the portion of bodies' energy which cannot be converted into useful work and dissipates in the environment in the form of heat. "I used the word 'entropy'," wrote Clausius, "to achieve more similarity with the word 'energy' inasmuch as the meanings of both corresponding quantities have much in common. Thus I believe they require homogeneous designations."

Having applied his conclusions to the universe, Clausius stated that two major principles of the mechanical theory of heat can be formulated as major principles of the universe:

1. The energy of the world is constant.
2. The entropy of the world tends to maximum.

If Thomson's conclusions aroused a certain discomfort, those of Clausius brought about a storm of protest. The new law, being so broadly interpreted, was only supported by theologists because it helped them to explain 'scientifically' the beginning and end of the world and the existence of a Maker. Other scholars either rejected the law completely, or objected to its application to the universe, or considered it superfluous and attempted to construct thermodynamics without it but with entropy! The latter idea was successfully developed by the Russian scientist N. N. Schiller and later by the German (of Greek origin) C. Carathéodory and T. A. Afanasyeva-Erenfest.

The novelty of the new law was rejected on the grounds that thermal phenomena were supposed to be analogous to mechanical phenomena and should therefore adhere to the laws of mechanics. G. Zeiner tried to prove this law in 1866. He compared the expression for the mechanical work performed to lift a body of weight $P = mgh/h = mg$ to the height h and the expression for the 'thermal work' performed to 'elevate the heat of a body' by a temperature T, and suggested that the ratio $S = Q/T = mcT/T = mc$ (where c is heat capacity) should be termed 'thermal weight'. Twenty years later, M. Planck pointed out that these processes should not be identified "because they are as different as the first and second laws of the theory of heat", and in the same way all forms of energy differ from heat which tends to dissipation and which is the cause of the irreversibility of processes.

The second law of thermodynamics and the notion of entropy facilitated a better assessment of the power capabilities of systems. Gibbs and Helmholtz had already proved that only a part of a system's total energy, ΔU (e.g. chemical fuel), could be utilized in a given medium (e.g. Earth's atmosphere). This part was termed the 'free energy', ΔF. Another part of a fuel's energy (the 'bound energy') is the product of the temperature of the environment, T_0, by the change in the entropy during a reversible process (e.g. as a result of the change in the number of moles of gas involved in the reaction), ΔS_0. This equation has the form $Q_0 = T_0\,\Delta S_0$. This part is transformed into heat and degrades in the environment. Thus the maximum work which can be performed by a system must not exceed the value $A_{max} = \Delta U - T_0\,\Delta S_0 = \Delta F$. Inasmuch as there are inevitable losses in real processes resulting from the irreversibility of $T_0\,\Delta S_{ir}$, the actual work is always less than the maximum work: $A_a = \Delta U - T_0\,(\Delta S_0 + \Delta S_{ir}) < A_{max}$.

The quantity of free energy is determined from the equality of the temperature of the system (T) and the ambient temperature (T_0), i.e. from the isothermality of the process of energy release. Therefore free energy, like energy, is a function of the state of the system: a change in it during a process does not depend upon the process but is determined by the difference between its final and original values. However, in reality, the ambient temperature and that of the system are usually different. The temperature in the combustion chamber of an internal combustion engine may reach 3000 K, for example, and that of the atmosphere does not exceed 300 K. The difference between the temperatures characterizes the store of thermal energy in the system.

The French physicist Georges Gouy (b. 1854, d. 1926) and the engineer A. Stodola (b. 1859, d. 1942) introduced the notion of technical working capacity: the maximum technical work a system may perform during the transition from the given state to the state of equilibrium with the environment, including the equalization of temperatures. In 1956 R. Rant used the same reasoning as Clausius did to introduce entropy and termed the above-mentioned quantity 'exergy'. The portion which was not converted into work was termed 'anergy'. The Gouy-Stodola principle is that the loss of energy resulting from the irreversibility of processes is the product of the ambient temperature by the sum of entropy increments in all bodies which take part in the investigated processes. Therefore exergy depends upon the ambient temperature and, strictly speaking, is not a function of the system's state, although it is conditionally regarded as such.

The energy of a system is composed of exergy and anergy. According to the first law of thermodynamics, the sum of exergy and anergy remains constant in all processes. The second law of thermodynamics implies that exergy decreases and turns into anergy in all irreversible processes. It remains constant only in reversible processes. Thus exergy—in contrast to energy which, strictly speaking, cannot be 'expended' or 'lost' (as the principle of conservation of energy reads)—is a measure of the working capacity of a system and decreases as work is performed or other irreversible processes take place. Consequently, the exergic efficiency of engines is the ratio of the consumed exergy to that supplied; that of heat exchangers is the ratio of the output exergy of the heat-transfer agent to the input exergy. For example, if the power efficiency of an internal combustion engine is approximately 35 to 40%, its exergic efficiency is 80 to 90%; if the power efficiency of a boiler reaches 92 to 96%, its exergic efficiency is between 50 and 60%.

The merits of exergy have made it very fashionable in recent years. But not everybody was aware of the fact that the exergic method of calculation only allows for losses during irreversible processes, which is not always necessary. Thus, theoretically reversible cycles of heat engines and the ideal Carnot cycle, which are absolutely different in design and efficiency, have the same exergic efficiency, i.e. 100%. As far as the technological consumption of heat (evaporation, metal melting, etc.) is concerned, the importance of exergy is insignificant.

When a gas is cooled to a liquid and then to a solid, the order of location and motion of particles grows, and entropy decreases. On these grounds, the German physicist and chemist Walther Nernst (b. 1864, d. 1941) formulated in 1906 his heat theorem, i.e. the third law of thermodynamics, which reads: if a chemical change occurs between pure crystalline solids at absolute zero, there is no change in entropy, i.e. the entropy of the final substance equals that of the initial substance (i.e. when the temperature T approaches 0 K, which is practically unreachable, the entropy S also tends to zero).

Entropy, Probability, and the Universe

The wise idea "there is nothing more practical than a good theory", which is often disputed by ignoramuses, belongs to the German scientist Ludwig Boltzmann. And this is not by chance. He bridged the gap between the second law and the theory of probability by connecting entropy with the notion of the probability of the state of a static system, an achievement which was of a great practical value. Events developed in the following way.

When the principle of degradation of energy was established, the Church took heart. If there was to be an entropic end of the world, there was, consequently, a similar beginning to it, therefore the Maker did, does, and will exist. So, God does exist!

In connection with Clausius' idea Engels wrote:

"...energy is lost if not quantitatively then qualitatively. *Entropy cannot be destroyed by natural means but can certainly be created.* The world clock has to be wound up, then it goes on running until it arrives at a state of equilibrium from which only a miracle can set it going again. The energy expended in winding has disappeared, at least qualitatively, and can only be restored by an *impulse from outside.* Hence, an impulse from outside was necessary at the beginning also, hence, the momentum, or energy, existing in the universe was not always the same, hence, energy must have been created, i.e. it must be creatable, and therefore destructible. *Ad absurdum!*"

In other words, attempts to apply the second law to the entire universe result in a disagreement with the principle of eternity of motion in the universe, which is expressed by the principle of conservation and conversion of energy. N. G. Chernyshevski, a Russian writer, said:

"The formula which predicts the end of motion in the universe contradicts the fact that motion exists presently. This formula is false.... The very fact that the end has not yet come makes it clear that the process was interrupted a countless number of times by a reverse process transforming heat into motion.... On the whole, it is a succession of vibrations, which has no beginning and no end."

No matter how convincing the arguments of the materialist philosophers were, physicists, the majority of whom adhered to elemental materialism, needed a weighty utterance from their own scientists. But they kept silent as they had no wish to come into conflict with the mighty clergymen and the idealist philosophers. Such a conflict could bring many troubles....

A certain revival came with the development of the molecular-kinetic theory of gases. One of the first papers on the topic was by the English physicist and inventor Sir Charles Wheatstone (b. 1802, d. 1875) and dates from 1845. He submitted a paper "On Physical Medium Consisting of Free and Elastic Molecules Which Are in Motion" to the Royal Society. However, they did not publish it, and the paper remained in their archives for 47 years! It was accidentally found and published by Rayleigh. It turned out that many of Wheatstone's findings had been rediscovered in the meantime. Such are the vicissitudes of scientific life!

In 1850 and 1851 Rankine and Joule published their works. But it was only in 1856 that the German physicist A. Krönig (b. 1822, d. 1879) published a consistent paper in which he introduced the notion of the chaotic motion of molecules and applied the theory of probability to physical phenomena. This forced Clausius to publish his research, which he had been 'nurturing' since 1850. He introduced the model of an ideal gas which had point-like particles and no forces of interaction between the particles. He also introduced the notion of the mean free path of molecules (from collision to collision) and derived a formula to calculate it. However, Clausius had assumed that the molecules move at the same average speed and this idea distorted the real picture.

In 1859 the Scottish physicist James Clerk Maxwell (b. 1831, d. 1879) managed to determine theoretically (using basis of the theory of probability) a density function, i.e. Maxwell's law for the distribution of molecular velocities, and was able to derive a more exact expression for the mean free path of molecules. This function is a parabola, with the vertex corresponding to the most probable molecular velocity. In 1866 Maxwell modified his law, and this progress inspired investigators to try to derive expressions for parameters of macrosystems, e.g. pressure and temperature, from very general ideas about the motion of particles. In 1920 Maxwell's distribution law was experimentally corroborated by the German physicist Otto Stern (b. 1888, d. 1969).

The Austrian physicist Ludwig Eduard Boltzmann (b. 1844, d. 1906) could not keep away from this problem. He was 21 years old when he wrote his first paper on this subject. The paper was titled "The Mechanical Meaning of the Second Element" but was purely mechanistic. Between 1868 and 1871 Boltzmann applied Maxwell's theorem to gases in an external force field (in the gravitational field of the Earth, for example, where each molecule is affected by gravity). Using this work, Boltzmann established a new law, that of the distribution of energies, and derived an expression for the function. The expression clearly demonstrates the opposite actions of gravity, which tries to keep molecules at the bottom of a vessel, and the thermal collisions between molecules, which push them upwards.

Molecular-kinetic theory revealed the physical meaning of absolute temperature and proved that it is proportional to the mean energy of the thermal motion of molecules. Hence, the motion should slow down as the temperature approaches absolute zero and cease completely when zero is reached. It was also established that each degree of freedom of a monatomic molecule (which has three such degrees, one for each coordinate) accounts for an energy of $\frac{1}{2} kT$, where k is the Boltzmann constant and expresses the energy-temperature relation ($\Theta = kT$).

The first theory of gases to take into account the size of the particles and the forces between them was developed in 1873 by the Dutch physicist Van der Waals (b. 1837, d. 1923). This theory helped to determine the size of molecules and could be used to calculate Loschmidt's number (the number of molecules per volume under normal conditions, i.e. when the temperature is 0 °C, and the pressure is one atmosphere), and Avogadro's number (the number of molecules contained in one mole of a substance).

In 1872 Boltzmann published a major paper called "A Further Study of the Thermal Equilibrium of Gas Molecules", in which he formulated and proved the famous H-theorem (the negative of H is an analogue of entropy). The integral expression of the theorem is inscribed on his tombstone, just like a sphere inscribed in a cylinder was engraved on the tombstone of Archimedes. The theorem states that an isolated gas initially in a nonequilibrium state approaches (in time) the equilibrium state, which is the most probable one. Whenever there is any alteration in the state of a gas, the function H most probably decreases, the probability that it can increase being extremely low. Boltzmann employed this theorem to prove that only his distribution law met the requirements of statistical equilibrium.

In the same work Boltzmann calculated the probabilities of various states of a system and proved that the most probable state is that in which the system's entropy is maximum. He proved that any process in a real gas (diffusion, heat conduction, etc.) will make the individual molecules interact in conformity with the theory of probability ... and concluded: "The second element is, consequently, a principle of probability." Hence, the second law is a statistical law inapplicable to the universe, the bodies of which do not move chaotically but are each subject to its own laws of motion. Moreover, the second law can be violated more often the fewer particles in the system and the slower their velocities.

Finally, in 1886 Boltzmann wrote: "...each distribution of energy corresponds to a quantitatively determined probability. Inasmuch as it coincides in practically imprrtant cases with the value which Clausius has termed 'entropy', we think it must also be designated by this term." Thus entropy was finally related to probability.

Boltzmann's works did not attract much attention at first, but between 1894 and 1895 a heated discussion of them broke out in *Nature*. Major blows were delivered by Loschmidt, Zermelo, Mach, and Ostwald. The first two were looking for defects in Boltzmann's H-theorem and claimed that the expression allowed H both to decrease and increase. Thus Loschmidt conjectured that if the velocities of all the atoms in the universe were reversed, energy process would proceed in reverse order. Mach and especially Ostwald were fierce opponents of any kind of atomism. Another distinguished American scientist, Robert Millikan (b. 1868, d. 1953), then remarked venomously that a reaction had set in against the kinetic theory and "led by this ram, the entire herd had started to jump backwards over the fence". Boltzmann defended himself quite skillfully but he was alone. Even Planck, an active opponent of Mach and Ostwald, did not share Boltzmann's ideas. "My reason for this," he said later, "was that at the time I considered the principle of degradation of energy to have the same significance as the principle of conservation of energy." This was the man who wrote in his autobiography that he could never prove anything new, no matter how strict and convincing his proof! He only changed his mind and supported Boltzmann in 1900, when he modified the expression for entropy to the form now used, viz. $S = k \ln W$, where k is the Boltzmann constant, and W is the thermodynamic probability (the number of substates a system can have, i.e. particle positions, velocities, and energies within a given macrostate as characterized by temperature, pressure, etc.).

Boltzmann was haunted by the animosity of colleagues and their misunderstanding of his ideas, and so he moved from place to place, acquiring a reputation as a restless and unsociable person. In 1869 he was appointed to the Chair of Physics in Graz but resigned three years later to work in a series of universities: Vienna, back to Munich, back to Vienna, Leipzig, and finally back to Vienna. Here he decided to remain. On September 5, 1906, the 62-year-old Boltzmann, who was always so full of creative energy, committed suicide in the resort near Abbazia where he used to holiday with his family. His work was only fully recognized in 1910 after Einstein had formulated, in 1905, the relationship between Brownian motion and kinetic theory and the appropriate functions corroborated by the French physicist Jean Perrin (b. 1870, d. 1942) in a series of experiments studied in 1906.

A comprehensive and complete system of statistical mechanics for gases, i.e. statistical thermodynamics, was developed (independently of Boltzmann and Maxwell) by a modest lecturer at the University of Yale (USA) called Josiah Willard Gibbs (b. 1839, d. 1903). His theory was far more developed than that of Boltzmann, but he advocated the same ideas. Gibbs published his articles in the journals of his college, and very few scientists were aware of either Gibbs' existence or his works. But even after he had become widely known in Europe, Yale did not recognize him for a long time (truly, no man is a prophet in his own country). Apparently, Yale's president once asked some European scientists for help in organizing the Department of Physics. The Europeans recommended Gibbs, but Yale's president had never heard of him.

Gibbs' entire and uneventful career was spent at Yale. He died in 1903 still working at Yale but having failed to gain the recognition of either students or staff. A year before he died he had published a book, but it had no influence on the arguments over Boltzmann's theory. The book was too mathematical and very few people could understand it. When it was reprinted to celebrate the 100th anniversary of its author's birth, it had to be supplemented by a 1700-page two-volume commentary! Only today are there readers who can appreciate it entirely. "Willard Gibbs is one of the greatest of American scientists and in fact created a new science between physics and mathematics," said Norbert Wiener, a fellow compatriot and the 'father of cybernetics'.

Thus the hypothesis that the universe would suffer a heat death was defeated. In contrast to the universal law of nature, i.e. the conservation of energy, the second law turned out to be a statistical law that is only applicable to systems consisting of a large number of chaotically moving particles. The law only indicates the most probable direction of processes. Processes which have low probabilities and proceed in the opposite direction are called fluctuations. They do not contradict the law; moreover, they proceed in conformity with it. But the law is inapplicable to individual bodies, particles, plants, and systems, as they are governed by their own laws of motion.

Is the Demon an Outlaw?

The struggle against the statistical interpretation of the second law of thermodynamics continued for a long time, and echoes of it can still be heard. Not very long ago the world famous physicist A. F. Ioffe said in a conversation with P. K. Oshchepkov, who was then looking for ways to concentrate the energy of dissipated heat,

"...I don't believe in God and don't consider him the Maker of the world. I don't know what did create the world, but I know for sure that it approaches a gradual equilization of every potential, the state of maximum probability. If somewhere in the world creation is taking place, it will have a probability so low that it can only be expressed by a one over one followed by eighty-five zeros. One cannot get around entropy."

However, the warm, sunny world, bathed in the green of vegetation and in the blue of the sky and water, palpitating with the joy of life, does exist and continuously consumes energy which somebody somehow accumulated! This means that there is a mechanism in nature due to which, and in conflict with the second law of thermodynamics, energy can be concentrated and entropy can be decreased. This means that the mechanism will be discovered some day, and now we may try to imagine it 'speculatively' as the ancient Greeks, for example, imagined atoms....

The first attempt in this direction was made by Maxwell in 1871. He invented an imaginary creature which was later called Maxwell's demon and endowed it with the functions of such a mechanism. The creature was so sophisticated that it could follow the motion of each molecule and determine its velocity. Having been placed beside a partition dividing a vessel into two sections, the demon could sort molecules by opening a door for fast and not for slow molecules. The result would be that the temperature and pressure in one section of the vessel would rise above those in the other, i.e. energy would have been generated, contrary to the second law, without any expenditure of work. More than 100 years have passed and the demon still lives, although he had been destroyed many times or banished.... First he was dismissed entirely. Clausius stated that the second law did not apply to demons and only regulates spontaneous thermal processes. Boltzmann denied that the demon could exist on the grounds that "if every temperature difference were eliminated, no intelligent creature could come into being". A similar view was shared by Einstein.

Yet interest in the demon continued to grow and people looked at him more closely. The demon turned out not to be as black as he was painted. Someone noticed that the demon performs work when he opens and closes the door and this work serves to accumulate energy. Moreover, as the Polish physicist M. Smoluchowski (b. 1872, d. 1917) remarked in 1912, the random thermal motion of the molecules must hinder the opening and closing of the door since the door itself consists of continuously and chaotically moving molecules; moreover, the demon himself is composed of molecules. Consequently, opening and closing the door can only be random and not subject to the demon's will. Therefore the second law remains unshaken.

Nevertheless, the demon's cute advocates found objections to these seemingly convincing arguments. The work performed by the demon could be less than the amount of energy generated, and the thermal motion of the door's molecules might not significantly disturb the controlled portion of molecules.

Then one of the creators of information theory, the French physicist Leon Brillouin (b. 1889, d. 1969), attacked the demon (between 1950 and 1960). He detected another flaw in the demon's work in that the demon could not trace individual atoms. The point was that Maxwell had failed to include radiation in the system which was in equilibrium at the temperature T (since he suggested the idea 30 years before the development of the quantum theory by Planck in 1900 and the formation of the thermodynamics of radiation). But the demon could not be able to see any molecules or control the door in the dark! Of course, if he were a demon or a particularly clever one, he would have other means of detection, perhaps by measuring the Van der Waals forces, or those due to electric dipoles or magnetic moments. But these forces are only apparent over short distances and the demon would detect some molecules too late to open the door without any work. Moreover, the force which helped the demon detect molecules would also have acted on the door and a certain amount of work would be required to overcome them. The demon has no other option but to use a flashlight.

The lamp would emit light, and therefore give off energy and lose entropy. The energy would be absorbed by the gas, the temperature of which is lower than that of the lamp's filament, and therefore the entropy increase of the gas would exceed the entropy decrease of the lamp. On the whole, the entropy of the system would increase. The demon is left with one final escape-route: he must detect molecules by the quantum of light they emit and his eye absorbs. This would also bring an increase in entropy, which the demon needs to obtain information on a given molecule (this will be discussed in the next section). The information is used by the demon to decrease the system's entropy which he does by opening the door for fast molecules and keeping it closed for slow molecules. However, strict calculations demonstrate that in this case the entropy of the whole system would increase as given by the second law since the absorption of a light quantum produces a greater increase in entropy than the decrease resulting from the ordering of the system. The temperatures would inevitably equalize, and the demon would not exist.

Despite the power of the above arguments, there may still be objections to it. The demon may be in form of a spring with a valve actuated by fast molecules and closed after they enter. Another approach is possible. Let us agree with Maxwell that a demon can really sort out molecules, thereby creating a temperature difference and decreasing the entropy of the gas. This would not violate the second law! This law is statistical and only valid for macroscopic phenomena; it does not follow the molecular level. If we consider only two molecules, they will settle in one section of the vessel 50% of the time. If there are many molecules, the probability that they all end up in one section is not excluded by the second law, it is only reduced to its minimum value.

How Much Entropy Is Contained in a Scientific Paper?

Everything depends upon the ratio of the new evidence (information) presented in a paper to the number of words. The period of heated discussion has passed, those physically dead have been buried, those morally dead have been renounced. People have noticed that the second law and entropy lead independent lives, as good neighbors, and permeate every sphere. Thus in 1929 Leo Szilard (b. 1898, d. 1964) and in 1943 Claude Shannon (b. 1916, d.) discovered the relationship between entropy and information.

Let us imagine a gas, the temperature of which approaches absolute zero. It has been solidified and all molecular motion has ceased; the position of each molecule can be determined. Thus in this state we know all about the gas, our information is at a maximum. As we remember, entropy approaches zero at this temperature. The connection is very simple: information is at maximum when entropy is at minimum. But at very high temperatures the positions of chaotically moving molecules are absolutely uncertain, and no information about them can be collected other than they are moving. Hence, information approaches zero in this case, and entropy tends to a maximum. Thus entropy (S) is proportional to the reciprocal of information (I), but information theory indicates (in conformity with the same law) that $I = k \ln W = -S$, where W is a value similar to thermodynamic probability. Hence, information is equivalent to the negative of entropy, and Brillouin proposed to term it 'negentropy'.

Thus if an entropy increase is a measure of the difficulty of returning a system to its original state, a rise in information is a measure of the difficulty of analyzing its substates, i.e. the positions, velocities, and energies of its particles. A lack of information about a system's substates means that energy, or negentropy, must be expended to return the system to a more ordered state.

It should be mentioned that information, as well as negentropy, is related to the system as a function of state and not to the intellect and memory of man as we are used to thinking.

The connection between thermodynamics and information theory also comes from the fact that the production and collection of information require expenditures of energy. In order to understand something (to utter a phrase, write it down on paper, etc.), we must expend energy, but we do not yet know what the quantitative connection between the energy expended and the information obtained is.

Assume that thermal energy is expressed, as usual, as $Q = T\,\Delta S$, and the work expended is $A = T\,\Delta I$ $(= -\,T\,\Delta S)$. The temperature here denotes 'thermal noise', i.e. disturbances which impede the transmission of information. The noise increases at high temperatures, and more work is required to overcome it. This adds another difficulty, since in order to determine the change in negentropy, we have to measure not only the amount of energy (work) but also the absolute temperature corresponding to the energy expended by the author, speaker, etc., or the thermal noise which disturbs the transmission.

These difficulties stem from the application of a method based on the superficial similarity between information and Boltzmann's formula for entropy to areas for which the latter was never intended. It is thus much easier for theorists to proclaim a relation between entropy and information than to demonstrate it by practical numerical examples. Nevertheless, 22 or 27 years ago this relation was so thoroughly developed that information theory became the basis (not vice versa!) for the development of a sophisticated system of universal thermodynamics (of reversible and irreversible processes), which was derived from a group of original equations (the theory belongs to M. Tribus, an American scientist). It should be said that before this, the thermodynamics of reversible processes (classical thermodynamics of ideal processes) and the thermodynamics of irreversible processes (real processes) each existed, but independently. The first considered every real process to be ideal, or reversible, and then the results were multiplied by experimentally established correction factors to account for their irreversibility. The second factors, such as the rate of entropy increase to take care of the irreversibility, are directly introduced into the initial functions. Experimental constants, e.g. thermal conductivity and emissivity, are required in this case too, but they are introduced from the very start.

So, how much entropy is contained in a scientific paper? If the paper contains a few pages and a lot of new information, the entropy is low; if the opposite is true, the entropy increases in proportion to the number of pages.

Love, Cybernetics, and Entropy

In the story *Love and Cybernetics* the characters, some tired women, dream about a cybernetic boyfriend who utters words such as 'an overpopulated country of loneliness', 'let us roast the deceased' (about a hen), and real human students recite a poem*:

> ...The grass of one-day joys
> Has hidden the violins of grasshoppers.
> The doubt has retreated to warm burrows.
> A tree has grown on the place of former luck.
> And calmness grew yellow and turned into a horse...

which is in no way superior to a cybernetic poem written by the RKA-301 computer and published in another book:

> All maidens cry like calm snows.
> This maiden will not cry by the bed.
> Rains are silly lovers but I am not shy.
> To stammer, to moan, to go, the girl was drifting
>   Under a sail and in the office.
>   Unpretended, fresh, deaf kisses
>   Are not too damp.
>   That girl is mute and tender.

Not much is left to do now. If only we could connect entropy with cybernetics, we could weigh love on the scales of entropy and describe it as a very unstable state....

* By G. Ball.

But first let us turn to cybernetics. In 1948 our scientific world was shaken by an incredible sensation: the science of cybernetics was born overnight, a science of control, communication, and processing of information. "Ban! Abolish!" yelled the learned opponents of all the leanings, "It is a pseudoscience!" But some years later science had to make room for the newcomer.

In 1948 *Cybernetics* was published by Norbert Wiener (b. 1894, d. 1964), an American mathematician, an 'infant prodigy'. The field of cybernetics had been prepared, of course (as had been the Copernican system, Newtonian mechanics, and the Mayer-Joule-Helmholtz principle of conservation of energy), by numerous achievements and findings in the natural sciences and technology, particularly the fields of automatic-control theory, radio electronics, the theory of probability, mathematical logic, the theory of algorithms, and the physiology of nervous activity. Wiener generalized and systematized all the new evidence to arrive at some completely new conclusions.

The branch of science formed in Wiener's mind first as a vague idea which later evolved into a complicated system crowning many years of mathematical and physical reasoning and research. The system made full use of Gibbs works on statistics. The book was still 'in the inkpot' when Wiener signed a contract with a publisher who was excited by the scientist's fantastic ideas about communication, automated plants, and the nervous system. The book was written in Mexico when Wiener was visiting the physiologist Arturo Rosenblueth (b. 1900, d.), whom he considered a 'coauthor' of the book since they discussed many of the relevant issues. The title was not decided immediately. The author wanted it to reflect the essence of the book which was "control and communication in animals and machines". The resultant title is of Greek origin: *kybernētēs* means 'pilot' or 'governor'. Thus we may consider cybernetics and entropy to be sisters because of their related origins.

Cybernetics is the science of control and communication. It is a general theory of control that is related to no concrete field but at the same time is applicable to all. This makes it similar to thermodynamics. Control (like the operation of a heat engine) is a closed process, i.e. a cycle which is performed over a closed circuit, consisting of a controlling unit, a controlled unit, and feedforward and feedback communication channels, which carry information. Control actions (commands) are in fact information about the actions required from the controlled unit. This is command information. Information on the state of the unit and other data coming from the controlled unit to the controlling unit is termed state information. Hence, control is the process of collecting, processing, transforming, and communicating information in order to perform actions. Any animate or inanimate system performing these functions is a 'cybernetic machine'.

The initial state of such a machine is uncertain and its entropy is at a maximum. As soon as the machine starts operating, it receives information which eliminates uncertainty, decreases variety, and makes the system's behavior predictable; therefore entropy decreases. The reduction of variety is one of the principal methods of control. There is a term in cybernetics called 'the entropy of choice'. This concept permits us to compare cybernetic machines with regard to their efficiency in the manner they carry out a purpose. The most preferable machines are those which require least information. All the rest suffer from message redundancy. Thus a man selecting a wife according to five criteria suffers a message redundancy compared to the man who chooses one using ... if, of course, this single criterion is sufficient.

It has recently been proved that an energetic approach to control (based on research into the flows and conversions of energy in control systems) is as efficient as an information-cybernetic approach.

Give Me a Plate of Negentropy!

Wiener said that enzymes may be Maxwell's metastable demons and decrease entropy. Brillouin, who was such an experienced information scientist and thermodynamicist, wondered how life and the second law of thermodynamics could be such similar examples of the impossibility of turning back the hands of time. This indicates the close relationship between the two problems. A plant, an animal, or a man is a brilliant example of a chemical system in a state of unstable equilibrium. They have an extremely improbable structure with very low entropy. This instability becomes especially clear after death. The second law of thermodynamics is a death sentence; it is cruelly and mercilessly enforced in the inanimate world, the world which is dead in advance. Life suspends this sentence and takes advantage of the fact that the verdict is passed without any fixed term of execution.

Erwin Schrödinger (b. 1887, d. 1961), a distinguished Austrian physicist and the author of a fundamental equation of quantum mechanics, attempted to answer these questions in 1943. His book *What Is Life from the Point of View of Physics* was a best seller, and zealous fans claimed it was on a par with the statistical thermodynamics of Gibbs and works by the founder of genetics, an Austrian biologist, Gregor Mendel (b. 1822, d. 1884). In fact Schrödinger had not 'discovered America' and similar ideas had been expressed before. But the author's name, the imposing title, and the yearning for fresh ideas after the war made the book extremely popular.

However, in 1935 the Soviet scientist E. S. Bauer published *Theoretical Biology* in which he expressed ideas very similar to those of Schrödinger, but using different terminology. Bauer formulated the three major properties of animate systems as a spontaneous alteration of the state (they resemble batteries, clocks, etc.), the counteraction of external forces, which would lead to an alteration in the original state of the environment, and constant work to prevent equilibrium with the environment. The first two properties may be found in other systems, but the third is the distinctive feature of animate systems. Therefore Bauer termed it a 'universal law of biology' with a clear thermodynamic meaning: the balanced state of inanimate systems is stable; the unbalanced state of animate systems is also stable. Animate systems carry free energy which may be liberated under certain conditions to support the unbalanced state.

Schrödinger also believed animate systems were out of balance with the environment. This imbalance is supported by a continuous exchange of food, water, respiration, etc. between the open animate systems and the environment. But exchange alone cannot achieve anything. Any atom of nitrogen, oxygen, or sulphur, for example, is as good as any other. Perhaps the object of the exchange is to absorb energy? But the energy in a mature organism is the same as that in any other quantity of matter, so replacing one joule by another changes nothing. And what about inanimate unbalanced systems?

If an inanimate system is out of balance with its environment and is isolated, its motion ceases quickly. Friction, heat conduction, chemical reactions, etc. will equalize the potentials, and will make the system collapse and become an inert mass in a state of thermodynamic equilibrium, i.e. maximum entropy.

Thus everything in nature (animate systems included) increases the entropy in its surroundings. Animate systems also gain entropy, i.e. produce positive entropy and approach a state of maximum entropy (death). Therefore the unbalanced state of animate systems is supported by extracting negative entropy (negentropy) from the environment. The purpose of metabolism is to release the positive entropy and extract the negative entropy. But the higher the entropy, the greater the disorder and vice versa. Thus the extraction of negative entropy is the 'extraction of order', enhancing the regularity of the organism.

There are two different mechanisms for producing ordered phenomena: a statistical mechanism which creates order from disorder, and another mechanism which creates order from a lower-level order. The principle of conservation of energy can contribute nothing to the explanation of these mechanisms. Apparently they must be explained on the basis of the second law. We know that mammals feed on ordered organic compounds; thus humans eat meat, potatoes, apple pies.... Having used up the orderliness in these foods, animals return them to the environment in a degraded, disorderly form to be assimilated by plants. The latter generate negative entropy from sunlight with the help of which the orderliness of the degraded substances is enhanced in their chlorophyll. This is photosynthesis, and the cycle is repeatable. This is the only natural spontaneous process on Earth in which entropy decreases owing to the expenditure of 'free' solar energy.

Since the degree of order of animate systems is capable of supporting itself and producing ordered phenomena, appropriate new laws should be enforced. These would be scientific laws and not those of a tenuous 'animate force', 'spirit', etc. The search for these regularities is at present involving biologists, physicists, chemists, and even engineers engaged in biophysics, biochemistry, and biomechanics. Humanity is likely to make its greatest discoveries in these very fields.

Therefore, if we wish to evaluate a soup or a piece of meat from the point of view of physical efficiency, we must use both units of energy and units of (negative) entropy.

The Queen of the World and Her Shadow in Time and Space

All the above-discussed phenomena concern the world around us. In the cosmos and in the world of elementary particles, where the velocities of bodies are commensurate with the velocity of light, the picture is much more complicated. As we have no room for a detailed discussion of this issue, we shall only consider the main aspects of it.

We know that matter exists in time and space. Time involves the succession of events but it is only one-dimensional. Space involves the arrangements of objects and is three-dimensional. According to Einstein's theory of relativity, in which gravitational forces act, time is a four-dimensional non-Euclidean space. Relations in a non-Euclidean plane (for example) may be described in terms of conventional Euclidean relations on curved surfaces. Einstein's work resulted in connection between space and time, which is expressed by the general notion of a space-time interval and a connection between material motion and its forms of existence in space and time. In other words, the flow of time and the extent of bodies depend on their velocities and the geometrical properties of space-time alter in the presence of a mass and its gravitational fields. If the velocity of a body approaches that of light, time 'slows down' and space is 'curved'. Thus classical physics' ideas with its concept 'absolute' (independent of moving matter) time and space were proved inadequate.

But in a world of conventional velocities, time and space are homogeneous (space is also isotropic, its properties being identical at all points). This means substituting different times, but leaving the material lengths the same, or negative space coordinates for positive ones into formulas, will not alter the result. Since space and time are forms of existence, the conservation of motion can be derived from their properties. Thus the principle of conservation of energy stems from the homogeneity (or symmetry) of time, since the flow of time cannot by itself cause a change in the state of a closed system, energy must be expended to do so. Similarly, the principle of conservation of momentum stems from the homogeneity of space, since a movement in any closed system does not of itself change the system's state, the change must result from interaction with other systems. The principle of conservation of angular momentum stems from the isotropy of space.

Therefore we may conclude that two measures of motion must exist simultaneously: a scalar measure (energy) and a vector measure (momentum). Classical mechanics does not relate space to time and so both measures exist independently. In the theory of relativity they come out as components of a universal measure of motion: a four-dimensional vector of 'energy-momentum'.

This brings us to the conclusion that the principle of conservation of energy can be violated in a non-Euclidean heterogeneous space-time. It is thus not surprising that Professor N. A. Kozyrev could hypothesize that the "flow of time may be a source of energy". The curvature of space-time may produce additional stress without changing the total momentum in the system "thereby changing its potential and total energy". The same issue was treated by Professor V. S. Gott: "Even now there are possibilities for discovering new forms of energy in the microworld and in the macroworld. There is a reasonable chance that new forms of energy will be discovered that generate solar radiation in addition to that produced by fusion reactions. New forms of energy are likely to be found in extragalactic situations."

However, this topic is very complicated and so far has been inadequately investigated. For example, recent evidence indicates that solar activity and the explosions in the nuclei of galaxies and quasars may not be explainable owing to fusion reactions. New sources of energy are being discovered as man penetrates deeper into the structure of matter and a 'vacuum energy' has been suggested. A space vacuum would thus be a superdense medium with a fine-grained structure, while conventional matter would be a rarefied state of this vacuum. At the fantastic density of 10^{93} g/cm^3 (calculated from this theory), immense gravitational forces would act between the grains of such a vacuum to cause such large local curvatures in space-time that the vacuum energy would be 'sealed' into the cells of the fine-grained structure and thus not manifest itself. To 'induce' a vacuum, matter would have to be compressed to an enormous density which under terrestrial conditions would demand an accelerator billion times more powerful than that at Serpukhov in the USSR. Therefore, the vacuum remains an absolutely inert 'emptiness'. The densities required are however created in space in bodies compressed by their own gravitational forces (in collapsars and a collapsed universe).

It is also assumed that new forms of space-time symmetry may be discovered. These would be more universal and would help us formulate a more comprehensive principle of conservation than that of energy, and yield a more comprehensive notion of energy.

The relationship of entropy increase to the direction of time is also interesting. Since the laws of classical mechanics are 'symmetric' for homogeneous time, we might assume that the 'symmetry' is conserved in statistics based on these laws. L. D. Landau and E. M. Lifschitz have proved this to be false. They concluded that "two directions of time are not equivalent in quantum mechanics and that the principle of degradation of energy may be a 'macroscopic' expression of this. So far, however, this connection has not been convincingly demonstrated and nobody has been able to prove that it does in fact exist".

Of all the known properties of bodies, entropy is the only one that alters unambiguously with time (increasing in closed systems). This fact is sometimes interpreted as the reason for the irreversible change in time from the past to the future. However, we should not forget that entropy is only one property of matter, and time is a universal attribute which manifests itself at all structural levels. Moreover, processes accompanied by an entropy decrease may occur in open systems (in living organisms, for example) and in the microworld. But in this case too time changes irreversibly from the past to the future. Even in a thermally closed system in which thermal equilibrium and maximum entropy are established with time, interactions between atoms, molecules, and other particles do not cease, nor do their indirect interaction with other objects via electromagnetic or gravitational fields or via neutrinos. All these processes occur over time. Therefore, an entropy increase cannot be considered to be the cause of time's irreversibility. The latter is caused, in fact, by dissymmetry—the irreversibility of causal relationships in all systems. If this were not true, the smoke and light from burned firewood, for example, could turn back into firewood, and the latter into trees which would disappear into the soil in the form of seeds.

On the whole, however, the general development of the world is a combination of cyclic and irreversible alterations—irreversible but not unidirectional. Matter can change beyond all bounds in various directions in an infinite material systems such as the universe. Consequently, the flow of time and the evolution of the world can never cease.

Entropy and ... the Construction Industry

We have seen how thermodynamics permeates even information theory, cybernetics, and biology via entropy and energy. But there are cases when thermodynamics is treated as a set of relations which have purely external similarities with thermodynamic processes and have nothing in common with either a change in entropy or a conversion of energy. These include, for example, 'the thermodynamics of production' or 'the thermodynamics of economics'.

This theory is based on the premise that epochs differ not by *what* is manufactured but by *how* it is manufactured, by what means of labor. From this, two principles can be logically derived and analytically written in the same way as the laws of conventional thermodynamics. But on the left-hand side of the first law (the principle of conservation of energy, as we know it) the amount of heat is replaced by "total labor costs for extended production" and on the right-hand side the change in internal energy is replaced by the "increase in labor costs for production" to which the "actual costs of socially necessary labor" are added instead of work. The "equation of state of economic production" is formulated by analogy with the equation of state of an ideal gas, i.e. the Clapeyron equation. And finally, the expression for the "entropy of economic production" is derived from the ratio of the increase in total labor costs to the abstract number of personnel employed in production.

The second law was introduced long before the first (treated at the end of the book and applied very rarely) as a "general law of nature" having a "direct relation to problems of political economy". Economic formulations of the second law (there are five) are given in Marx, who never thought they would have any relation to thermodynamics not to mention the construction industry! Thus the first reads: "No matter what the form of production process is, it should be a continuous process, i.e. pass periodically through the same stages." The third formulation reads: "No society can continuously produce, i.e. reproduce, without the continuous conversion of some of its produce into the means of production or into elements of new production." And further we read: "The thermodynamic character of these formulations by Marx is evident. Indeed, if the production process is continuous and its stages pass periodically through the same states, such a process is treated in thermodynamics as a circular and therefore a reversible one." (!)

Finally, an ideal economic cycle ("a combination of economic processes and parameters, which secures the greatest actual wealth, i.e. the greatest cost of surplus products") is derived by analogy with Carnot's ideal cycle of heat engines. And so forth.

We can only admire the comprehensiveness of this thermodynamic approach, the logical development of which is crowned by a general theory of systems. Only a purely intuitive application of the latter to the construction industry could account for such an original result

Thus Energy and Entropy were born during the devel opment of science, technology, and production They have not only permeated the bases of the scientific and technical revolution, given birth to a Queen Among Sciences (Thermodynamics), they have also employed the latter to construct the foundation of a new generalized method of reasoning and scientific research: the general theory of systems.

The march of the Queen of the World and Her Shadow over the Earth is gaining momentum and penetrates practically every sphere; it has the potential for a great leap towards the life of humanity. The anticipation of this sometimes generates a certain pessimism. Yet there are many reasons for optimism, the more so since each day brings us new discoveries that expand the rule of man over nature.

Is Humanity in a State of Siege?

Having analyzed every aspect of the industrial revolution for the last 200 years, the English philosopher and economist Arnold Toynbee (b. 1852, d. 1883) answered 'yes'. Our objective is far less complicated: we shall consider the ratio of the rapid consumption of power resources to the increase in entropy of the environment and the latter's pollution by noxious waste.

Some resources, such as the Earth's vegetation, are renewable, but in some cases, if measures are not taken, their regeneration may be limited and a crisis ensue even before the nonrenewable resources are exhausted. The transformation of resources into raw materials, manufacturing, transportation, and every other process, including life, can only be carried out at the expense of energy, the resources of which are limited.

One of the first publications on the issue of the capacity of power resources to meet increasing demands dates from 1912 and was written by N. A. Umov. His paper "Objectives of Technology in View of the Exhaustion of Energy Resources on Earth" was a quantitative analysis based on the development of power engineering in the developed European countries, Russia, and the USA. The analysis contained all the elements of modern forecasts, such as estimates of the explored resources (coal, oil, water power, etc.), estimates of their utilization factors, estimates of the growth in demand for power (6% per year), estimates of the available reserves (for 100, 200, and 500 years), and a breakdown of where energy is used, viz. 50% goes to mechanical energy (70 to 80% of which is used by transportation), about 27% goes to heating, 20% to metallurgy and technology, and about 3% is consumed by 'illumination', i.e. the generation of electric power. The analysis also included an assessment of the efficiency of engines (6 to 8% (maximum 25%) for steam engines and 33 to 35% for Diesel engines) and heat-utilizing units (30% for heating systems and 40% for technological equipment), and so forth. Umov called for the maximum utilization of the power of rivers whenever water fell by between 220 and 950 meters. "The annual power that running water on the Earth generates has been assessed at 1 to 2 billion horsepower, which is three times greater than the current demand for mechanical energy. But this power is only 50% of the total energy consumed on Earth, therefore this source cannot support modern civilization." Then Umov dealt with the possibilities of utilizing the wind, tides, waves, the internal heat of Earth, and solar energy. He pointed out that the "utilization of the power of tides is in fact a utilization of the energy of the Earth's rotation. Harnessing it would cause the Earth to rotate gradually, more slowly, and lengthen the day. However, even if our annual production of energy from this source was a hundred times over present consumption, the day would only shorten by one second in ten thousand years". Umov considered that the Sun would be the ultimate source "from which humanity would draw energy to support its civilization and development in the distant future". With great insight, he was confident that humanity would master solar energy not with the help of thermal but "with the help of a different process, the nature of which would probably be electric. In this field everything is yet to be created, but we have several centuries to settle the question".

In the 73 years since Umov's forecast it has only been proved wrong in that the epoch of oil and natural gas has come and is passing rapidly, the era of nuclear power has come and will last for a long time, the efficiency of heat engines has increased to greater than 40%, while steam engines have been ultimately forced out by turbines and internal combustion engines. However, the renewable resources remain almost unused, as before, although extensive research is under way.

The reserves of fossil fuels would have been exhausted long ago if new deposits had not been located. The quantity of oil and gas consumed between 1950 and 1963 was equal to all the reserves located before 1950. But the deposits discovered during the same period were four times the 1950 reserves. On the other hand, it is quite difficult to estimate the exact extent of located reserves because the 'economics of extraction' from the Earth and from beneath the ocean is assessed differently by different authors. As a result, "...some specialists believe that the reserves of nuclear fuel are fifteen times greater than those of organic," Academician M. A. Styrikovich writes, "while other experts, in no way less qualified, claim that they are fifteen times less."

This is hardly surprising since the current criteria of the 'economic expediency of extraction' is expressed in monetary units, and money units are so unstable that an adequate assessment of the actual expediency is not possible. The only accurate criterion is the ratio of energy contained in extracted resources to the total energy of resources used for extraction (represented by depreciating equipment and material costs and equating them to directly consumed energy). In this case the actual power efficiency of extraction will be assessed. The efficiency of extraction rises in proportion to the extent the ratio exceeds unity.

Power production doubles every ten to fifteen years, the assessment for the year 2050 being 700×10^{12} kWh. This is the amount of energy consumed by humanity throughout its entire history! But even this figure is only a part of the energy that can be generated from the renewable sources of energy: sunlight, running water, wind, and the heat of the Earth's interior.

To compensate for the shortage of material and power resources, exotic projects have been suggested so that man can utilize the mass of other planets and even ... that of the Sun. Large planets are mostly composed of hydrogen. Thus the mass of Jupiter (2×10^{27} kg) would generate 10^{39} kJ when converted, by fusing hydrogen into helium, into energy. If we released 4×10^{23} kJ per second (which is equal to the power of solar radiation), this would suffice for almost 300 million years! Other projects involve surrounding the Sun by a sphere of radius of about 150 million km. The sphere would be a populated shell and all the energy radiated by the star would be utilized. Coming down to Earth, we should mention that if a tenth of the world's landmass (Antarctica excluded) were covered by solar power stations with an efficiency of 20-30% (twice that of vegetation), the power obtained would be equivalent to that of 60,000 (6 million kWh) electric power stations.

Soviet scientists from the Pushchino Research Center have designed a food-supply factory housed in a 10-storey complex, a greenhouse with a square base 70 km long! The factory would yield several crops per year and feed 450 million people, but it was estimated to cost nine trillion rubles to construct! Great hopes are placed on chlorella, a water plant with a photosynthesis efficiency approaching 25%. The biomass of this plant grows sevenfold daily. One hectare of sea surface could produce over 40 tons of dry chlorella per year..

Energy degrades in the form of heat and sometimes carries deleterious wastes and radiation. Regular and 'tangible' matter degrades by being transformed into less orderly waste. These wastes heat and pollute the environment. These two factors will limit the production of power and the manufacture of goods.

An increase in the CO_2 content of the atmosphere impedes the release of heat into space and thus elevates the temperature on the Earth. An increase in the heat expelled from power plants has the same effect. On the other hand, an accumulation of dust in the atmosphere reduces the Earth's temperature. An elevation of the average air temperature by a mere two or three degrees may cause the polar ice cap to melt, and catastrophic effects would ensue, while a 1-2% decrease in the heat supply to the Earth's surface is enough to cause the advent of an ice age. Therefore Academician N. N. Semenov calculated that the production of fusion energy should not exceed 5% of the solar energy reaching the Earth. This volume of production would only be 600 times the modern level (4.7×10^{13} kWh).

The material world has evolved in the part of the universe which is known to us. The development proceeds from more to less ordered states, from heterogeneity to homogeneity, from concentrated energy to degraded energy, from low values of entropy to high values. But in the remote past the reverse must have taken place. If this were not so, the material and power resources could not have been accumulated on Earth or in the Solar system. So, is it possible that a time will come when these processes will again proceed naturally? Or will a way to induce them artificially be discovered? Even now energy is concentrated and entropy decreased, although slowly, during natural photosynthesis, which gives life to Earth. This process supplies humanity with 80 billion tonnes of organic material per year, which is ten times the total quantity of fossil fuels (coal, oil, gas) extracted during the same period. It is thus not surprising that the Nobel laureate, atomic physicist F. Joliot-Curie believed that "it is not so much atomic energy as the mass synthesis of molecules similar to chlorophyll that will be responsible for the real revolution in world power engineering". Artificial photosynthesis is now a major objective of science.

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ENERGY and ENTROPY

With the discovery, between 1845 and 1847, ofthe principle of conservation of energy, the importance of energy for human life and progress was recognized, and scientists gave energy the romantic name of `The Qleen of the World'.

Some twenty years later scientists discovered entropy, a measure of the dissipation of energy.
This book outlines the history of the formulation of these two notions.
Ideas and concepts that were crystallizing in the human mind for thousands of years as the result of observation, practical experience, and developments in technology are described, together with philosophers, scientists, engineers, and inventors who contributed to their formulation.

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