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Point of View

Mathematical Modeling and the Philosophy of Science

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Abstract—Philosophical and methodological aspects of predictive mathematical modeling are considered. Predictive mathematical modeling in the epoch of technological challenges to postindustrial society is becoming a third way of cognition, supplementing and uniting classical theory and natural experiment. The author describes conceptual, architectoral, and technological problems of creating an integrated software environment for high-performance solutions to interdisciplinary direct and reciprocal new-generation problems for multiprocessor petascale computing systems with scalable parallelism. Trends are unfolding in the development of "neoinformatics" with the introduction of cognitive principles into the automation of model and algorithm building and into the creation of decision-making systems for a wide range of users from various production and social spheres. Constructive and infrastructural principles are proposed for the development of an open basic modeling system that supports all basic stages of science-intensive computer experimentation and is oriented at an effective long-life cycle and coordinated development by various design teams.

Keywords: high-performance computing, mathematical models, algorithms, third way of cognition, technological stages of modeling, integrated instrumental environment, applied software architecture.

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Pandora's mathematical jar. The problem of interpreting and purporting mathematics appeared to have been solved already by the great Galileo, who announced that "physics speaks the language of mathematics." However, in the 21st century, humanity plunged into the whirlpool of technological revolutions, and mathematics, a modest servant of all sciences and opposite informatics, began to turn from a Cinderella into a bossy tsarina. Today humans fall victim to the race of mobile gadgets, the expansion of social networks and the Internet, computer game addiction, cyberterrorism, and other virtual realities. This is only the beginning of grand transformations, since the materialized epoch of postpetaflop supercomputers and the future advent of "exaflops" with an inconceivable 10^{18} operations per second are fraught with the new postindustrial epoch of "cloud-based" computing, digital design, 3-D printers, military game strategies, "smart" homes and cities, electronic governments, and other innovations, designed to upend our ideas of the surrounding reality.

F. Goya in his suite of etchings *Los Caprichos* showed a horrifying picture of how "the sleep of reason produces monsters." In a similar situation, it is necessary to draw on, according to Hercule Poirot's recipe, the resources of the "little grey cells" and analyze prudently the role of science in generating trends that characterize "this mad, mad, mad, mad world" (as the famous film director S. Kramer formulated accurately). Within this article, the objective is concretized as follows: we will be interested in philosophical aspects of mathematical modeling of various processes and phenomena, since it focuses on the great potential of scientific and technological progress. Before we consider this topic, it is necessary to undertake at least a brief historical journey, as well as to reserve the definitions of key concepts.

Mathematical modeling is the study of processes and phenomena using mathematical methods. Each of the categories given in the above definition requires substantive unlocking. The processes and phenomena are primarily implied to be real: technical, natural, or social. Examples are the production of metals and new

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materials, natural or anthropogenic disasters, and demographic dynamics. However, the study of abstract models represented by pure mathematical objects is also topical. Moreover, this happens in reality: a physical (chemical, biological, etc.) model is represented by a mathematical model, in which insignificant effects are practically always ignored. The competent construction of a model is the objective of the *modeller* (the term *modeller* is used to denote a specialist engaged in modeling in a specific applied area).

The next concept that we have to work with is extremely capacious and raises serious debates, *mathematics*. Academician V.I. Arnol'd pushed ardently for the unity of theoretical mathematics and theoretical physics, which he equated. In addition, he, in fact, rejected computational mathematics and informatics, calling them "pedestrianism" in his polemical works. Arnol'd's principal, although extramural, opponent was A.P. Ershov, the author of truistic terms such as *computer literacy* and *school informatics*, who would proudly say of himself, "I am a mathematician." In this article, we will mean by mathematics a triune structure that includes theoretical mathematics, computational mathematics, and mathematical modeling. This division into three components fully corresponds to the most general definition of mathematics as a science of mathematical objects, although, of course, widespread concepts such as *applied mathematics, computational informatics, computational geometry, topology,* etc., also have every right to exist. In the English-language literature, the word combination *computer science* is in common use, and its word-for-word translation into Russian, meaning computational sciences, hardly takes root in Russian. To finish the terminological clarifications, note also numerous names such as *computational physics, computational chemistry, computational biology,* and others. These disciplines should rather be classified as the application of mathematical modeling to various subject areas.

The origin of the history of mathematical modeling should at least be referred to those times immemorial when Egyptian priests predicted solar and lunar eclipses, which was impossible without shrewd computations. If we speak about knowledge classification, only one science existed initially, philosophy; division by specialty began in the Middle Ages after the appearance of alchemists and metaphysicians; however, traditionally, even in our time, all European scientific degrees are called *doctor of philosophy* (PhD). Later, natural sciences oozed out into independent and rapidly developing trends, which generated their industrial epochs, and philosophers, thanks to great personalities like F. Bacon, I. Kant, G. Hegel, B. Russel, N.A. Berdyaev, and many others who grasped interrelated processes of cognition, as well as of economic, technical, social, and personal development, became the generators of general humanistic ideas.

From the second half of the 20th century, the role of scientific and technical progress changed cardinally: as a result of basic research, the world saw missile-borne nuclear weapons, which not only had political consequences but also made urgent the issue of the very existence of humanity. This problem was solved on the principles of mutually deterrent parity; however, Hamlet's dilemma "to be or not to be?" will continue to be topical for at least the next few decades. One cannot but give an example of the use of mathematical modeling in nuclear security. In 1996 the nuclear powers signed the Comprehensive Test Ban Treaty. France was the last to ratify this agreement only after completing a computer program that modeled nuclear tests with a high degree of confidence. Moreover, it is an open secret that all countries of the "nuclear club" constantly modernize this weapon, but field tests are fully replaced by computational experimentation.

In recent decades, the civilized community has plunged into a new anthropogenic revolution, this time associated with rapid computerization. The past 50 years have seen a high-accuracy implementation of Moore's law (Moore is a cofounder of Intel), according to which the computer capacity increases by 1000 times every 11 years. In 2008, humanity entered the era of postpetaflops computers (10^{15} arithmetic operations per second, or flops), and by 2019, in line with Moore's law, the advent of an exaflops computer is expected, which will comprise hundreds of millions and billions of computing devices. This will lead to the transition from quantity to quality and will shake up our ideas of supercomputing. Surprisingly, the exponential growth of performance does not close in on the expected satiety, and Moore's law holds on: in 2016, the Chinese Sunway Taihu Light led the list of the world's top 500 most powerful computers with values of over 125 petaflops; that is, to reach the predicted indicator of 10^{18} operations per second by 2019, the performance should increase by only eight times.

Military history always deals with the opposition of the sword and the shield: the development of offensive and defensive weapons is closely interwoven. The same picture is in the scientific and technical sphere: superproblems appear simultaneously with the appearance of supercomputers: "appetite comes with eating." The 21st century is characterized by fantastic progress in all sciences and technologies, and in two-to-three decades, humanity will herald a technological singularity with inexhaustable energetics, new materials, eternal youth, and even immortality. One way or another, the future problems cannot be met without supercomputer modeling. It is becoming a third way of cognition and, in full agreement with Academician M.A. Lavrent'ev's prediction, which he made 50 years ago, is already a mediator between theoretical and experimental research.

Over the past 20 years, humanity has lived through two shocks, which have sharply changed all productive, social, and personal relations: the appearance of the Internet and then the mobile phone. Let us pose a question: what will be the third technological shock? Our forecast is global modeling. The arguments are simple. The first two "cataclysms" were associated with the informational side of computer evolution. Indeed, the growth of computer performance is approximately proportionate to the increase in the capacity of operational memory and throughput of data transfer channels, and their great capabilities underlay new information technologies. However, it was forgotten that the computer was initially designed for computing and not for work with big data. This fantastic potential of high performance computing (HPC) is destined to become a catalyst of predictive high-resolution modeling both for obtaining new basic knowledge in all sciences without exception and for creating new-generation production technologies during the transition to the VI economic pattern, which is expected by futurists. Here it is advisable to quote the frequently cited phrase of D. Wince-Smith, the former president of the United States Council on Competitiveness: "The country that wants to outcompete must outcompute."

This article has a philosophical and methodological trend but does not pretend at all to conceptualize professionally and philosophically the problems of scientific cognition, which have broad coverage in the literature [1–4]. Valid problems of mathematics and modeling are also discussed in the author's articles as well [5–16]. Interestingly, Academician G.I. Marchuk's scientific and organizational legacy, whose unique experience was generalized in his posthumous publication, is of an exceptional value for understanding the problems under study [17].

"What is truth?" Tradition has it that these were the words that the Roman Procurator of Judaea Pontius Pilate addressed to the seditious Christ. Dubious Pilate made a fatal decision and, shrugging off responsibility, washed his hands symbolically.

Two concepts, revealed in this drama, are of key importance for mathematical modeling: *truth* and *decision making*. The first category is very rich in content and characterizes the results of human cognition. The goal and content of modeling is the study of processes and phenomena, which can be designated by the philosophical category of *object*. Note that meaning can be absolute or relative. The latter means that our information on an object under study or subject area is approximate with a few exceptions that prove the general rule. For example, a dilemma that has occupied the minds of the best theoretical physicists in recent decades is whether or not the Higgs boson exists. The answer to this question affects the acknowledgment or negation of the so-called Standard Model, which determines the basic ideas of structures and interactions between the microworld and the universe. Another visual illustration is an image recognition problem, which belongs to informatics but has various applications: space, seismic, and other big data processing; object identification ("friend," "foe," or pertaining to another group); antimissile defense; automatic text or speech signal analysis; etc.

As a rule, the objects considered are characterized by certain quantitative indicators: spatial dimensions and shapes, temporal intervals and velocities, substance masses and densities, and other properties, which can be measured in various units. Here we cannot do without the definition of the *error*, or *accuracy*, of model representation. A quantitative characteristic φ of a studied object can be taken as the accurate, or true, value, unlike an approximate value $\tilde{\varphi}$ derived from modeling. In our case, it will be a computer experiment, often including a solution of a complex computational task, and the *absolute error* of the numerical result obtained will be the difference $\delta = \varphi - \tilde{\varphi}$. If error δ is sufficiently small, modeling as a cognition tool produces a good description of an object (one can say, a high accuracy, or resolution, or predictiveness); otherwise, the description is bad. We are not going to focus on the mathematical rigors and formalities of classes of the functions φ and $\tilde{\varphi}$; we demonstrate the philosophical statement that the path to truth is hard and slow. First, let us note that the concept of the acceptability (or unacceptability) of a method by accuracy is relative. We may say that one method is more accurate than another, but we cannot draw a clear-cut boundary that divides methods into suitable and unsuitable (now we are not speaking about the price of a method, this important issue will be covered later). Then, the value of φ, which we assume as a real characteristic of an object, is derived from field observations and measurements, since practice is known to be a criterion of truth. However, measurements themselves are inevitably made with errors, which can be significant, and the improvement of methods that obtain reliable results in various subject areas forms separate topical scientific trends. In addition, field experiments are sometimes too difficult or even impossible, and then "internal" criteria of high fidelity modeling have to be applied. A typical approach comprises the use of various models of an object under study, including hierarchical ones, and comparison of the results of individual numerical experiments.

A modeling error generally consists of at least three components:

$$\delta = \delta_n + \delta_m + \delta_c,$$

where δ_n is the error of the object model (e.g., physical); δ_m is the error of the mathematical model; and δ_c is the error of the computational model. For example, the viscosity or density and ambient temperature variations are often neglected in problems of hydrodynamics, greatly simplifying the problem but leading to an error in the physical model δ_n. Another crucial circumstance is that various numerical data that determine the material and geometric properties of an object are known approximately, as a rule.

Various mathematical setups can be used for an already selected object model: in the solvable functional equation, $L\Phi = F$, operator L can be differential or integral or it can have a variational form; the descriptions of its coefficients and definition area may also differ, conditioning various δ_m values. For example, a huge amount of meteorological and space information is used in weather forecast problems, and the problem of "data assimilation," so that the data do not contradict the model used, is a serious research trend. Also note that solution Φ of a mathematical equation is represented by functions (pressure, density, temperature, etc.) dependent on the spatial coordinates and time and value $\varphi = \varphi(\Phi)$ is another functional, obtained as a result of some indirect measurements. Qualified comparison of φ with Φ values is an issue that requires special competence.

The numerical error δ_c depends on many factors: the method of discretizing the initial continuous task, the method of approximating functional equations with algebraic ones, the computational stability of algorithms used, and the characteristic features of a specific machine arithmetic. Computation with the accuracy δ_c necessary (and sufficient) for practice is the prerogative of contemporary computational mathematics. Its founder, Academician and Russian Navy Admiral A.N. Krylov, taught 100 years ago that computing with unnecessary scrupulous precision is a gross professional mistake, because it appreciates the work. A characteristic feature of numerical methods is the use of a family of algorithms that depend on computing parameters that predetermine the output error. Typical is the generation of sufficiently dense grids in computational domains with characteristic step h and the use of methods of approximation of the initial equations, such that if $h \to 0$, asymptotically the error is proportionate to value h^γ, where constant $\gamma > 0$ is called the order of the algorithm. Then, as the grid is refined, the *method converges*; i.e., approximate solution $\tilde{\Phi}$ approaches true Φ, and error δ can theoretically become arbitrarily small.

From knowledge to wisdom. There is a popular belief that Western civilization is based on knowledge and Eastern civilization, on wisdom, the latter notion implying actions based on personal or foreign experience. Moving over to the second category, to which we paid attention in the story about Pontius Pilate, "decision making," let us place the alternative "knowledge is wisdom" in the context of the current problems of modeling and not cultural and geographical differences.

The immediate goal of modeling is either obtaining new basic knowledge (here it is appropriate to recall the saying "there is nothing more practical than a good theorem") or studying the properties of various processes/phenomena: scientific–technical, natural, and social. However, obtaining knowledge is not a goal in itself; the "bottom line" of modeling should be decisions predetermined by a specific sphere of activity. Computerization of the intellectual sphere of decision making is a very tempting idea, and approaches to its implementation lie in the building of *decision-making systems* [18]. Here we may recall another courageous idea: how to build a theory of inventive problem solving [19].

Since mathematics is simultaneously a servant and the tsarina of all sciences, its universal language is applicable practically everywhere. It has long been known that the level of development of any industry depends on the degree of its mathematization and, today we may bravely add, computerization. We may call a happy circumstance the fact that a relatively small set of basic mathematical objects and operations with them, just within several tens, can describe a wide variety of processes and phenomena. For example, a relatively simple and well-known equation, which bears the name of the French mathematician S.D. Poisson, is used successfully to solve problems of thermal conductivity, diffusion, electromagnetism, gas dynamics, etc. Certainly, specialists from the above scientific–technical fields have different professional training and even psychology, and, for each of them to benefit significantly and practically from modeling as a mathematical innovation, significant preparatory work should be done. It should be realized that the actual tool for the abstract user under consideration is a computer with installed software. Specific representations of these technologies are of great importance (the devil is in the details).

The increasing general cognitive role of modeling in the English-language literature is reflected in the appearance of new concepts: *simulation, data mining, deep knowledge, digital design,* etc., which, as well as the above-mentioned term *computer science,* have not yet found their popular analogs in Russian. However, overall, the observed trends show the formation of a new-generation science of knowledge, which will develop its own cognitive technologies and ontological principles (see the review in [20]) and improve artificial intelligence tools. Artificial intelligence is of special attention. It is clear that computers are nothing without human beings, and a machine works only by a prescribed program. However, as computer resources, memory, and computing capacity grow extraordinarily, the catastrophic lag of programmers' labor productivity has become a weak link, which may be classified as a global programing crisis, especially application programing. The only visible "light at the end of the tunnel" is qualitative growth of the automation level of mathematical modeling and algorithm development, associated one way or another with the creation of a natural "language factory." A. Kleppe's vivid and witty book [21] designates this paradigm as a shift from *paleoinformatics* to *neoinformatics*.

We will not ask the sacred question whether a machine can think, because we are interested in a more down-to-earth problem: is it possible to build a modeling system that would solve wide classes of topical tasks with high performance? The answer to this question comes immediately as a sharp negative, because universality and efficiency have always been in an antagonistic relation. However, we will see in the next section that hard-to-hit targets can be hit if the problem and approaches to it are viewed from an unexpected angle.

Technologies are key. To make modeling an efficient tool for obtaining new basic knowledge and a real productive force, it is necessary to carry out a tremendous job in science-intensive programing, computing and information technologies, and, just as important, the creation of state-of-the-art organizational structures with cooperation between teams of designers and users. The characteristics of the current situation make it impossible to improve modeling in the absence of not only R&D networks, i.e., various combinations of research and design jobs, but also industrial highly reliable (robust) and highly productive software products.

To imagine the scale and content of this problem, let us look at it from different points of view or in different systems of coordinates. On the one hand, modeling issues can be classified by industries that predetermine the main vectors of flows of human and financial resources: machine building and energy, nature management and the chemical industry, biology and medicine, construction and transport, agriculture and so on. Simultaneously, all objectives to be met here can be divided according to their mathematical setting. The sets of equations of Maxwell (electromagnetism), Navier–Stokes (fluid dynamics), and Lamé (elastoplasticity); the equations of heat and mass transfer and multiphase filtration; and the systems of quantum mechanics and Boltzmann's kinetic theory—all these formalisms are characterized by rich internal systematization and simultaneously by the presence of various formulations as differential, integral, and/or variational correlations. The most practically valuable and at the same time the most complex are interdisciplinary problems, which describe interactions of heterogeneous processes or phenomena and represent the totality of various functional equations.

All mathematical problems are also divided into direct and reciprocal. The direct types comprise relatively "simple" problems: all initial data are known, and they require the desired solution. Reciprocal problems, on the contrary, contain unknown parameters to be defined by additional conditions, including the minimization of a preset objective functional and meeting certain limitations on data properties. The solution of a reciprocal problem is based on multiple computations of direct problems during the directed sorting of parameters using the extensive theory of optimization methods. Reciprocal problems proper, particularly within the computer-aided design of certain devices, the optimization of equipment's operating mode, and numerous setups with the identification of a model's parameters (problems of geological exploration or image recognition belong here), are most valuable for an engineer and any productionist.

The diversity of mathematical problems is ensured by a great number of computing methods, the global flow of publications on this topic is huge; therefore, we are not going even to simply enumerate the main trends. However, we cannot but focus on important concepts such as *bad, good,* and *the best* algorithm. Let us introduce the following definition: a method is called optimal for solving the required class of problems with the desired accuracy for a given computer system if it yields the result under minimal resource expenditures. Thus, even for a fixed set of algorithms, various ones can turn out to be the best depending on the problem type, assigned output errors, and the computer used. This means that the best is the enemy of the good: an attempt to optimize a method in a specific case, as a rule, will be more expensive than the solution done by any of the existing acceptable methods. Consummate professionalism is of special significance here; it is an essential condition to conduct a computational experiment competently. For example, the necessary stage of a computational experiment is algorithm verification, which proves that the problem set will reliably be solved with it. Otherwise, attractive results may turn out to be nothing but computer artifacts, irrelevant to reality.

Another very important issue is computational and information technologies for solving big (including interdisciplinary and reciprocal) problems on supercomputers. First of all, this means huge amounts of application software, which can be developed only through international cooperation between many developer groups. It is very important to utilize the opportunity of reusing the available software products that concentrate a colossal intellectual potential accumulated over many years. An obvious condition for creating mathematical modeling tools is also the high performance of state-of-the-art multiprocessor computer systems (MCSs) with a sophisticated architecture of heterogeneous processor devices, which use distributed and general hierarchical memory. By happy coincidence, a clear-cut division of technological stages exists in the ocean of modeling problems and algorithms (geometrical and functional modeling, discretization and approximation of the initial problem, etc.), which can be developed fairly independently based on the agreement of intermediate, or interface, data structures.

To date, there are many commercial and publicly available application software packages (ASPs) for solving certain classes of mathematical modeling problems in the global market. However, the strategic concept of new-generation computer tools is to create an integrated long-life computational and information environment with participation of a wide range of developers in close interaction between scientists and engineers. The formation of the resultant basic modeling system (BMS) should meet the following research and production principles:

• flexible extension of the composition of computer modules with automated building of new mathematical models and algorithms (this condition is natural due to the continuous development of computational methods and technologies);

• adaptation to the evolution of computer platforms with high-performance algorithm mapping on the MCS architecture;

• efficient operation within cloud-based computing technologies at shared computing centers with web-based access.

The ultimate goal of the BMS under consideration is transition from the artisanal production of individual ASPs to the industrial manufacture of applied mathematical and software support based on a systems approach and common tools, which will increase by many times the productivity of the development and use of end products.

Quo vadis? The answer to the question which goal justifies the means necessary to implement the megaproject under consideration is obvious: it is mass demand for modeling practically in all spheres of human activity. However, the issues of the tactics and strategy of control over socioeconomic processes that will inevitably arise in the future epoch of postindustrialization still await deep realization, including philosophical understanding.

So what awaits us? Let us start our consideration with the top level—the image of an encyclopedist scientist. Theoretical physicists L.D. Landau and R. Feynman complied with this image, the whole world studying their textbooks at the end of the 20th century. In recent decades, scientific disciplines have become so complicated and specialized that one person is unable to master all the necessary knowledge. The sheet anchor in this situation is the supercomputer: it can provide for not only any reference information but also solve a problem practically immediately (with visualization), which, using "old technologies," would require long hours and days of scrupulous analytical investigation. Consequently, a "new-formation" scientist—both a theoretician and experimenter—receives a powerful intellectual helper; still the final word, let us stress, remains with man.

Here it is appropriate to draw an analogy with computer chess. In 1974, the world's first computer chess software championship was held in Stockholm, which was won by the Russian program Kaissa. Earnest bets were even made then whether the machine could ever catch up with chess masters. Now the best programs have already beaten world champions, and professional players cannot even think of preparation for tournaments without a computer. However, its use during competitions is strictly forbidden. In this situation, Grand Master G.K. Kasparov suggested an alternative sport, "live chess," in which "man + computer" pairs compete (this idea has elicited no response from the sporting public).

The problem of supercomputation has another aspect, energy costs. One of the main factors that check the advent of the exaflops computer is high energy consumption, which, by a pessimistic estimate, reaches 100 MW; i.e., the functioning of such a powerful computer requires the operation of a small power plant. The task that the best engineers face is to reduce this figure to 20 MW. Thus, mathematical modeling is a sufficiently expensive affair. Curiously, a possible way out of this deadlock is mathematical, and it consists in building "cheap" algorithms. The job of a computer is to perform arithmetic operations and transfer data. Communications not only slow down the process but also are its most energy-intensive component. Hence, the task is to create algorithms that need the smallest amounts of information exchange.

The topic "mathematics should be economical" suggests lengthy and diverse discussions. For example, with what computer accuracy should arithmetic operations themselves be implemented to guarantee the correctness of the numerical result but not to perform superfluous work? Standard architectures imply computations with the so-called simple and double accuracy, when 32 and 64 bits (binary digit bits) are correspondingly allocated for a machine word. It is clear that such a solution is palliative; ideally, arithmetic with a variable digit capacity should be introduced to tune automatically into the requirements of a problem. Such intelligence of computer hardware is not science fiction at all; work has long been aimed at creating field programmable logic devices (FPLDs). This field can even make the mathematician's holy grail come true: the appearance of a computer "customized" for a problem or an algorithm. The stumbling block here is again the combination of the finances and the commercial competition of computer platforms. If these issues are solved, we will be able to see how computers will begin to create their kind; i.e., they will actually design new computing devices, giving a handle to new philosophical reflections.

The situation with the potential mass user of modeling computer systems turns out to be somewhat clearer than with their designers. However, it has far-reaching social consequences. The easiest way is to consider industries associated with computer aided design systems (CADSs). Such systems materialize in various products that have well-known English abbreviations, CAD, CAE, CAM, PLM [21], which provide for advanced technologies of computer, or digital, engineering. CADS products have long been converging in this sphere with modeling software systems, forming a single production cycle: product (airplane, automobile, etc.) design documentation is entered into a computer, where the necessary computations are optimized, and the results are output again in factory formats and go directly, for example, to numerically controlled machines. In addition, expensive and long aerodynamic, as well as strength and crash, field tests can be reduced, ultimately yielding a significant economic effect. In such conditions, obviously, qualitatively new requirements arise on the preparation of practically all engineering and technical personnel, and the prospect of new mass professions becomes a reality.

The same is also true of other high-tech industries involved in key spheres: the development of nanomaterials, biotechnologies, new geological prospecting and mineral extraction methods, energy saving, etc. We are speaking about not only "fashionable" innovations, with which contemporary scientific and technical progress is associated, but also traditional fields like agriculture, which cannot stay away from the change in productive relations.

The current technological shocks require social perception, the works by philosophers and futurist thinkers (e.g., T. Kuhn [23] and R. Kurzweil [24]) associate such processes with the categories of *scientific revolution, reason evolution,* and *postscience*. Technically, the above road can be covered in a short historical time, and the main problem that arises here consists in preparing new personnel—a whole generation of specialists in supercomputing and extreme mathematical modeling. This requires new training programs and courses in a wide range of disciplines for supercomputer education and retraining courses for mature specialists and training personnel. In fact, the objective is to overcome one of the consequences of Moore's law: the emerging personnel deficit in the world. Societies that will apply the necessary efforts to overcome it will enter the road to the "bright future" of a supercomputer civilization.

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