FROM THE HISTORY OF PHYSICS

The style of a scientific creative genius—Yakov Il'ich Frenkel' (on the eightieth anniversary of his birth)

V. Ya. Frenkel'

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The celebrated French natural historian G.-L. Buffon is credited with an aphorism that has come down to us as the catch-phrase "The style is the man." Buffon's remark actually reads somewhat differently,[1)] and its intent was that the individuality of a writer or poet is manifested not in his selection of subject, not in his formulation of the problem, but in the manner in which the fundamental idea (which is universal property—an author may borrow it and may not take umbrage if it is borrowed from him[2)]) is elaborated and solved.

It seems to us that the above rephrasing of Buffon might also be applied to appraisal of creativity in representatives of the natural and, in particular, of the physical sciences. Although the representatives of the natural sciences investigate subjects of the same nature, the circle of ideas that they advance to explain the behavior of their subjects can also be included in the notion of a scientist's style of thought. (Full correspondence with Buffon is restored when we speak of exposition of the attainments of a specific branch of science within the framework of the corresponding course, be it a course in theoretical physics, mathematics, general physics, etc.)

To what degree is the creative manner of, say, a theoretical physicist individual? In this article, we shall carry through an analysis of this kind using the scientific career of Yakov Il'ich Frenkel' as an example. Our use of the term "creative manner" (style) will embrace not only his personal approach to solution of problems or to their very formulation—the method by which they are treated, the selection and construction of adequate models to describe the process studied, the appeal to various mathematical formalisms to describe it—but also the manner of exposition, i.e., the style of the scientific publications.

In 1934, in his capacity as head of the theoretical physics department at Leyden University, Prof. H. Kramers delivered a traditional speech that he had entitled "Physicists as Stylists"[1]. He dedicated it to his predecessor, Paul Ehrenfest. Kramers observed correctly that the traits of Ehrenfest the man were reflected in the very structure of the scientific papers of this unique scientist, and that they identified their author at once by their very style and sound. A reader who was familiar with earlier papers by Ehrenfest could easily tell that a new paper was his, even if the author's name were concealed from him. Here we have a perfect analogy to the situation that is characteristic for literary and artistic works—provided, of course, that they are products of brilliance.

In a discussion of such matters, Frenkel' would stress the curious paradox that creative individuality—this symptom of originality and departure from the standard—once manifested and established, itself becomes to some degree a standard with a limited number of degrees of freedom. "The individuality of a creative personality," he joked, "can be tested by determining whether it is possible or impossible to parody it." Senior staff members of the Physico-technical Institute (FTI), where Frenkel' worked for more than thirty years, recalled how in 1924, during the Fourth Congress of Russian Physicists, Frenkel' delivered a masterful parody of Ehrenfest, the host of the meeting, and how, at one of the after-hours gatherings of the FTI staff in the early 1930's he launched into an astonishingly droll "self-parody," i.e., he parodied himself.

During recent decades, publications in physics have become increasingly dry and have developed a kind of common language that is just as faceless as the language of mathematical formulas is impersonal (as Kramers had stressed). One of the causes of this trend has perhaps been the improbable rise of the flood of publications. The feeling has developed as a result that "ornamentation" of scientific papers, which was so brilliantly done in the works of the old masters of the Seventeenth through Nineteenth centuries, has become superfluous.

Although concise exposition of a problem, revelation of the facts, and stripping of excess verbiage from the truth are not without their own reason and esthetics, the other approach to presentation of the results of research also has its advantages and justification. In working on his papers, Frenkel' probably was concerned not only with going from the formulation of the problem to its solution by the shortest path, but also with making his train of thought as accessible as possible to understanding. Here we see the lecturer who is accustomed to speaking to an audience. It is as though he transferred the devices that he used in oral presentation of his material to its written exposition.

"Personally, I do not consider it necessary to couch my books in the awkward language that results when everything that might bring it to life and improve communication of the sometimes dry material has been carefully leached out of it. The right to use metaphors should not be the monopoly of poets; it should also be shared by scientists," he wrote in the late 1940's. This is why Frenkel's papers are easily read and well remembered. In March of 1947, Max Born wrote to him, "I thank you for sending the copy of the paper on fission. I read it with great interest, although I am not a specialist in nuclear physics. You always write so clearly and simply that it is easy to follow your thought."[2]

Quite typically, a number of Frenkel's papers that originally appeared in scientific periodicals were included bodily in a collection of his popular-scientific papers that was published as part of the USSR Academy of Sciences series "Popular Essays by Classic Authors in the Natural Sciences"[3].

Frenkel' would stress that he admired not the harmony and virtuosity of rhythm in Mayakovskiĭ's poetry, but the remarkable, unexpected and precise similes and metaphors that would impress themselves at once and for all into the memory. It is no surprise that he himself enriched the physical literature, the language of physics, with numerous long-surviving images.

Before relating these, however, let us list a number of terms that are now widely used in the physics literature and were introduced into it by Frenkel'. It would be interesting, for example, to go through the subject indexes of physics monographs and attempt to recover the names of the scientists who made "terminological" contributions—each in his own field of science. Thus, a recently published American paper[4] attempted (quite successfully) to answer the questions implied in the title of the article "Who named the 'on-particles'?" This paper includes a summarizing table of the names of scientists who discovered "on" particles (those whose names have like-sounding endings taken from the word "electron") and those who were their "godfathers." Frenkel's name appears three times in this table: he introduced the now widely-known concept of the quantum of excitation (1931), which he named the exciton in 1936. In 1932, in his "wave mechanics" he proposed that Tamm's acoustic quanta (1929) be called phonons.

The concept of the "hole" has gained very wide currency in contemporary physics. This word was originally (in the early 1920's) introduced into the physical literature by the British physicist Griffiths, who is known for his work in solid-state physics. Griffiths applied the term "hole" to macroscopic cavities in the interior of solids; they were the centers of structural imperfections that gave origin to the cracks that "sheared" specimens (these cavities are now known as "pores"). In a study of diffusion in solids, Frenkel' proposed that the name "hole" be given to something quite different—a vacant site in a crystal lattice, i.e., the lattice center left by an atom that has gone over into an interstice. Thus, according to Frenkel', the interstices composed a kind of reservoir for ordered atoms; in his papers, he speaks of a "lattice of interstices." The concept of the vacant site—the hole—has been extremely productive and has acquired full citizenship. The term "hole" as used by Frenkel' (see, for example,[5]) has found its way not only into specialized physics handbooks and encyclopedias, but also into ordinary dictionaries (such as Webster's). The combination of a hole in a crystal lattice and an adjacent interstitial atom is called a "Frenkel' defect" (and sometimes a "Frenkel' pair"[6]). Frenkel' slyly referred to the energy required to form such a defect as the "heat of pairing." [Untranslatable pun: the same Russian word denotes also "evaporation heat"—transl.]. He used the same lighthearted term in his lectures at the Polytechnic Institute for the 1-MeV energy necessary to produce an electron-positron pair.

In 1939, Frenkel' authored an article in which he developed an approach to the study and calculation of a nucleus of a new phase within an existing phase. He called these pioneers of the new phase (droplets of liquid in a gas, minute crystals in a liquid, etc.) "heterophase fluctuations"—a term that is also frequently used today.

We do not have the opportunity here to examine in detail all of Frenkel's terminological novelties and windfalls, and shall end our far-from-exhaustive listing with the figurative expression "collectivization of electrons," which he uses for facile description of the stripping of valence electrons that accompanies condensation of metal vapor, the transfer of these electrons from the "sole" proprietorship of their respective atoms to the collective that has been known since Drude as the electron gas (it is interesting to note that the phrase "collectivization of electrons," which, it would appear, should be specific for our country, has also entered the English-language physics literature).

Let us turn now to a description of the models and images that were developed and proposed by Frenkel', and recall some of them by way of illustration.

Let us begin with examples that pertain to the description of solids and liquids. Comparing their structures, Frenkel' wrote: "If each block in a wooden pavement has the same number of neighbors, and if the pavement can be likened in a sense to a crystal, then the illustration for a liquid might be a cobblestone pavement whose stones have inconstant numbers of neighbors. There is more room in a liquid for movement of atoms than there is in a solid. When a crystal melts, its volume increases by 3—5 and as much as 10%. This volume increase results in much livelier movement of atoms from one equilibrium position to the next as compared with what we have in crystals, where the atoms are squeezed almost to the breaking point.

"The comparison with a streetcar that has been overloaded to the possible limit holds here to some degree. It is only necessary for one or two passengers to step out for the others to have greater freedom of movement."[3]

Explaining the appearance of the so-called Schottky defects, uncompensated atoms in an interstice between vacant crystal-lattice sites (which therefore differ from the Frenkel' defects introduced previously), Frenkel' introduces the figurative notion of absorption (or "swallowing") of the vacancy. This metaphor explains the following process: an atom departs for an unfilled new plane that is abuilding at the surface of the crystal, and the empty space left behind it, the hole, is filled, leapfrog-fashion, by atoms from deeper-lying planes: the vacant site diffuses into the crystal.

We noted above that the very notion of holes in a crystal and their motion is due to Frenkel'. In the late 1920's and early 1930's, he arrived at a far-reaching generalization in the electronic theory of semiconductors (holes in a filled Brillouin zone) and elementary-particle physics (positrons as holes in an ocean of states with negative energy—after Dirac).

In 1936, Frenkel' wrote that a crystal can be regarded as a kind of solid solution of holes and dissociated atoms (i.e., atoms in interstices) that becomes the more concentrated the higher the temperature.[7] This later gave rise to the idea that it might be possible to "precipitate" this solution. And it has in fact recently been shown that holes can be coagulated to form the very pores that Griffiths had once called "holes."3)

Why do liquids offer no resistance to shear? Professor A. G. Samoĭlovich recalls how Frenkel' put this rhetorical question at one of his lectures. He asked his listeners to produce a matchbox and then demonstrated how it offered resistance to attempts to shift parallel planes relative to one another. But then he removed the inner box with the matches, repeating the attempt on the empty "case" alone. The planes shifted without effort—the case went from a rectangular parallelepiped to an oblique one. "The liquid did not resist shear either, because it contains cavities" explained Frenkel'. For all of their arbitrariness, such explanations greatly facilitate exposition and are forever remembered.

In 1946, Frenkel' read a course of lectures on the theory of metals. Soon thereafter (in 1948) it was published in the form of a separate book. The "Introduction to the Theory of Metals" has already gone through four Soviet editions and has appeared in six foreign translations. Even the titles of some of the sections of this book are telling. Here is the "Three-Atom Model of the Crystal and its Stability:" with a linear chain of three atoms as an example, it is shown how, with increasing temperature of a solid and the thermal expansion that accompanies this increase, its crystal lattice becomes unstable—how the local failures that herald the transition of the crystal to the liquid state make their appearance in it. Another section: "The Two-Atom Model of the Solid" (!). Here, using a two-atom example, he demonstrates the transition to repulsion between atoms as a crystal is compressed from the attraction that is characteristic for their interaction when the crystal is first placed under tension.[8]

S. I. Pekar notes that "Sometimes it is not even a model, but only a well-conceived, lucid, figurative expression of Frenkel's that has become the formulation of a problem later solved by other theoreticians. For example, in 1936, in the 'Journal of Experimental and Theoretical Physics,' Frenkel' wrote (in a treatment of the local distortion produced by an 'excitation quantum' or exciton in the crystal lattice in which it moves.—V.F.): 'Here the light particle behaves as though it were dragging a heavy load of atomic displacements behind it.' Pekar continues: "With this picturesque comment, Frenkel' anticipated polaron theory, which has been developed since 1946."4)

In the posthumously published paper "Theory of Reversible and Irreversible Cracks in Solids"[9], Frenkel' stressed that cracks that exist in a solid (before it is loaded) must represent free surfaces that gradually move together until the distance between them has become equal to the normal distance between neighboring atomic planes. "From the purely geometrical standpoint," writes Frenkel', "these normal distances between neighboring layers of particles might be treated as cracks, and then any solid could be considered as interlaced in all possible directions (in particular, crystallographic directions) by a system of cracks of atomic width." To this typical metaphor, we might append an interesting modelling device that has been used to calculate the kinetics of crack development. Frenkel' treats the crack as a horizontal plate (beam) that has been split into two parts and comes under the action of a distributed load (cohesive forces) and, at its outer end, a concentrated load (tensile force).

In the mid-1940's, Frenkel' did a great deal of work in the field of atmospheric physics. Wishing to stress in one of his papers that clouds are not by any means congealed formations, but objects that are in a state of dynamic equilibrium (between evaporation and condensation), he compared them to candle flames, which are, of course, immobile and unchanging only at first glance[10].

Professor Ya. E. Geguzin remembers a lecture that Frenkel' delivered at Khar'kov in the spring of 1939[11]. Frenkel' had just completed a study of the electrocapillary fission of heavy nuclei. To explain how a neutron "triggers" the fission reaction, he brought up this analogy: at the blackboard, he drew a picture of a water faucet with a drop hanging from it. In the absence of external disturbances, it is in a state of equilibrium, held in place by capillary forces. It is only necessary to tap the faucet (and Frenkel' tapped his picture) to dislodge the drop from it. Recalls Geguzin, "I can still hear that tap on the blackboard as it broke the silence of the packed auditorium."

Another picture that Frenkel' drew in his classical paper on electrocapillary fission of nuclei is also universally recognized: the droplets of charged mercury which, on reaching a certain potential (charge) not only do not merge with one another (as we are accustomed to observing in the case of uncharged mercury drops), but, to the contrary, move farther apart.

If we continue with our discussion of Frenkel's nuclear-physics work from this standpoint, we may find another scientific metaphor in his notion of nuclear temperature—which he introduced in a 1936 paper that appeared immediately after Niels Bohr's famour paper on the compound nucleus.5) Frenkel' regarded the absorption of a neutron by a nucleus as condensation of the neutron (and the approximately 8-MeV energy that a slow neutron introduces into the nucleus as an energy of condensation), and the escape of a nuclear particle as its "evaporation" from the nucleus, a process in which an energy of evaporation is expended.

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It might, however, be stated that in the last two cases we are no longer dealing so much with typical Frenkel' figures of speech in the description of phenomena (stylistic features of his papers) as with his distinctive style of thought, as manifested in his extensive use of analogies in the solution of physical problems. It is characteristic that even in his first published paper, which was devoted to the kinematics of the automobile differential, he should, in writing the equations of motion of the wheels (which are coupled to the drive shaft through the differential), find them to be quite identical to those that determine the electric currents in two inductively coupled circuits. And he goes on to analyze his equations successfully in "electromagnetic" terms—in the analogy with the equations of electric-circuit theory[12].

The method of analogies interested Frenkel' not only from the standpoint of its possible applications, but also in a more general, philosophical aspect. He devoted a series of papers to this problem (a paper by Frenkel' on this subject was published in 1970 on the basis of a surviving expanded summary of one of these papers, which he had read in 1931[3]). Frenkel' writes vividly and at length of the method of analogies in the Foreword to the first volume of his "Wave Mechanics: "For didactic reasons, I have made wide use of the method of analogies in this exposition; though sometimes superficial, they have the advantage of lucidity... An analogy, if approached with the necessary caution, is the straightest and clearest path from the old to the new; but it must not be forgotten that any analogy, unless it is actually an identity, has certain limits. Nothing truly new is ever implicit in the old, and in learning the laws of nature we must learn to see not only the old in the new, but also the new in the old, regarding the latter as an approximate form of the former."[13]

Writing in their Foreword to Frenkel's selected papers on the theory of electrons and atomic nuclei, I. E. Tamm and Ya. A. Smorodinskiĭ placed special emphasis on their nature as a "... model of how a physicist who has worked long in classical and statistical physics approaches a new problem, and how an analogy, correctly understood, can lead us to a generally correct interpretation of a new range of phenomena."[14]

That Frenkel' could use his favorite method of analogies with such success was due precisely to the fact that as a romantic among scientists he had a lively and active interest in a whole series of fields of physics that stood quite apart from one another. This enabled him to see that which apparently unrelated phenomena had in common, to get to the cause of the similarity by the use of devices that had been developed successfully in another field.

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Frenkel's name comes up very often in a recently published exchange of correspondence between A. F. Ioffe and P. S. Ehrenfest.[15] Ehrenfest, who had high appreciation and encouragement for Frenkel's talent, did much to popularize the latter's work abroad. At the same time, during the 1920's he would stress (sometimes even with a certain exasperation) the difference between his and his young Soviet colleague's approaches to physical problems. Thus, in a letter of the 14th of August 1924, he wrote that "Frenkel's pattern of thought differs so greatly from my own that I have no hope for any helpful mutual influence: to him, "results" are infinitely more important than "understanding:" thus far, almost nothing has come of our conversations. Only Pauli might be able to tame him, since he thinks clearly on his feet"[15].

Needless to say, the word "understanding" in this phrase of Ehrenfest should not be taken in its primitive (literal) sense. New and general principles of developing theories are very often built on quite marshy ground. Only much later are these theories shored up with a strong foundation containing the minimal number of noncontradictory axioms. For a scientist with Ehrenfest's critical acumen and talent, it is these searches for fundamental axioms and rigorous proofs of intuitively hazarded theorems and conceptions that constitute the essence of understanding. Without this understanding and elucidation, Ehrenfest obviously did not consider it possible to work on applications of new theories for solution of specific problems. Frenkel', on the other hand, believed that the most important criterion for the correctness of new theories should be nothing other than the successful solution of old problems and the statement of new ones with their aid. This is why these "results" were, in Ehrenfest's (probably correct) opinion, more important for Frenkel' than Ehrenfest's "understanding."

As an example, let us cite the concept of the de Broglie waves, which was advanced in 1924. Unexpected and paradoxical, it at first appeared invalid to many: how could the notions of electrons (whose "granularity" no one doubted) and waves be combined in a single entity? Commenting at Leningrad on de Broglie's paper, which had been read at Frenkel's theoretical seminar at the Physico-technical Institute, Ehrenfest said half-seriously that: "de Broglie or I—either one or the other of us has to be cracked." Frenkel', who was first in our country (as observed by I. E. Tamm) to recognize the fruitfulness of de Broglie's idea, applied this relation not just to free electrons, but to description of the behavior of electrons in a metal, and used this conception as an aid in deriving all of the positive results of the Drude-Lorentz electron-gas theory. In addition, he calculated the free path l of electrons in a metal, comparing it to the coefficient of absorption μ of electronic de Broglie waves in a crystal ($l \sim 1/\mu$), a quantity that had been calculated neither in the classical theory nor in Sommerfeld's quantum theory, which was based on the new quantum statistics.6) The conception that Frenkel' developed also made it possible to understand the influence of temperature on resistivity (the scattering of electronic waves on density fluctuations, which increase with temperature) and the role of lattice distortions or foreign impurity inclusions in it.

An attitude similar to Frenkel's in his approach to the "understanding-result" problem was also characteristic for Enrico Fermi, and he also came under well-meaning criticism from his colleagues for it. The American physicist Morrison recalls that Fermi usually discussed advances that had already been scored, while Bohr, on the other hand, concentrated his attention on that which had not yet been done and was presenting difficulty. Telegdi remarked on the same subject that "I think Fermi—if we speak of philosophy rather than style—was always a pragmatist. A theory was all right as long as it explained facts—and to the devil with philosophical ornamentation." This prompted Pauli to call Fermi the "engineer from quantum mechanics"[16].

Frenkel' liked to repeat to his students, who sometimes found it difficult to accept quantum-mechanical conceptions in their conflict with so-called common sense (which has been trained into our subconscious by everyday experience in dealing with the "understandable" laws of classical physics) that "to understand something is to get used to it." His quick and agile theoretical physicist's mind and his surprising intuition reduced this habituation time to a minimum.

In giving their due to his quickness to respond and to the tolerance for new ideas that is so typical for the scientist with a romantic bent, we do not by any means intend to disparage the efforts of scientists of the other persuasion, who devote their talent to casting light on these new ideas, which at first seem to be confused and groping for the truth. The efforts of scientists of these two types are not so much contradictory as complementary, illustrating the validity of Bohr's complementarity principle.

It is interesting to note that Ehrenfest's view of Frenkel's approach to physics problems can be contrasted to the following judgment from D. I. Blokhintsev:7) "Frenkel' placed the understanding of a physical phenomenon ahead of everything else. I have never been able to escape the impression that once having understood a phenomenon, he lost interest in it. The later fate of an idea that he had set loose was of little interest to him. He was even less concerned with extraction of any gain from his achievement. The pleasure of discovery was apparently reward enough for him."

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In the first detailed bibliographic article on Frenkel', which was published in this journal in 1962, its author, Igor' Evgen'evich Tamm, wrote: "In the classification proposed by Ostwald in his book 'Grosse Männer,' Frenkel's scientific bent was that of the perfectly typical 'romantic' scientist."

Among the various traits characteristic of the "romantics," Ostwald listed diversity of scientific interests—the ability to work simultaneously in several quite remotely related fields of their science. And this was to a degree typical for Frenkel'. Referring by way of example to the range of his scientific interests and projects as of 1938—1939 (the years that were most productive in terms of numbers of publications), we find papers on statistical physics and the physics of the condensed state (heterophase fluctuations, diffusion, plastic deformation, the physics of polymers and emulsions, the mechanism of muscular activity), quantum mechanics and the theory of superconductivity, classical physics (the general theory of oscillations of mechanical systems), nuclear physics and the breakdown of dielectrics.[8)] Blokhintsev feels that the diversity of Frenkel's scientific interests was to a substantial degree a reflection of the tendency that he had observed in Frenkel' to lose interest in problems that he had solved.

This evaluation is the more interesting in that it can also be applied to other physicists, e.g., to Tamm. Late in the 1950's (when Tamm was immersed in his work on the general problems of quantum mechanics), I happened to mention in a conversation with him how frequently references were being made to his "Tamm surface levels" in connection with the then rapidly advancing development of transistor physics. I found that Tamm had forgotten all about the paper in question.

Returning again to Frenkel', I recall a "semilegendary" episode that was related to me. He had been asked to attend seminar activities of the senior-course students in the Physico-mechanical Department of the Polytechnic Institute. At these sessions, students would deliver abstracts of various typical papers. Frenkel' entered the auditorium just after one of these essays had been started. Having finished, the student answered questions put to him. Frenkel's question began: "I came in a bit late and I don't know whose paper you are telling about..." and followed with a series of critical remarks on its content. In his answer, the student, to the surprise and gratification of those present (including Frenkel') identified the paper as one of Frenkel's that had been published a few years previously.

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It is necessary to devote some attention specifically to Frenkel's attitude toward mathematics. This subject was his "first love" in science. At the age of 16, he generalized the theory of series and arrived at a new method of calculus, which he called "progressive." Young Frenkel's work won high marks from Petersburg University Professor Ya. V. Uspenskiĭ (a student of A. A. Markov), who perceived in it the fundamentals of the calculus of finite differences. This calculus is associated with the names of Fermat, Newton, and Leibnitz and dates from the end of the Seventeenth Century. The independent approach of the schoolboy to the springs of the calculus of finite differences could be regarded as a major triumph, but any satisfaction that he might have felt was probably tempered with embarrassment: after all, it had turned out that he had been pounding at an open door... However, Frenkel' kept his sympathy for mathematics and continued to study this science diligently. As an example, he taught a course in higher mathematics during the 1920's in the Physico-mechanical Department of the Polytechnic Institute and tutored students in the subject. As one of them—now Prof. O. M. Todes—remembers it, this was a physics course, in which the fundamental concepts and formulas of higher mathematics were taught not in the abstract, but in their relation to concrete physical problems. Frenkel' believed that this was the only way to teach elementary courses in higher mathematics at the technical colleges. In his early youth, he had studied a two-volume mathematics course written by the remarkable physicist G. A. Lorentz, and this may have been a decisive factor in the shaping of these ideas. A year before his death, Frenkel' was planning to start work on a collegiate mathematics textbook in which he would commit to paper the methodological ideas of the course that he had taught during the 1920's.

In a 1946 presentation on the contemporary state of the theory of metals (at the First Kurnakov lectures at Moscow), Frenkel' stated his views on the "mathematical accompaniment" of physical theories, with some recourse to hyperbole: "The more complex the system at hand, the simpler must its theoretical description necessarily become. It is necessary to demand of a theoretical description of a complex atom, and even more so in the case of a molecule or crystal, that the results be as precise as those from the theory of the simplest atom, the hydrogen atom... In this case (that of complex systems—V. F.), all that is required of the theory is correct interpretation of the general nature of the quantities and laws pertaining to such a system. In this respect, the theoretical physicist is like a cartoonist who must reproduce his original not in all of its details, like a camera, but simplified and schematized in such a way that the most characteristic features are revealed and emphasized. Photographic accuracy can and should be required only of the theoretical description of elementary systems. A good theory of complex systems should be only a good "caricature" of these systems, exaggerating those of their traits that are most typical and deliberately ignoring all of their other—nonessential—properties." Stressing his basic argument once again, he adds that "a good caricature of a person cannot be greatly improved by more accurate and precise depiction of nontypical details of his face and figure"[17].

Frenkel' followed this program. Detailed numerical calculations appear embodied in tables and diagrams only in his early papers; approximate estimates and illustrative figures appear in the later ones (beginning with the second half of the 1920's). In a commentary on a dissertation, he wrote (in 1939): "The author's numerical calculations are exceedingly complex. We are amazed by the writer's patience and persistence in laying a road through a whole forest of expressions... I would have decided against such a feat and looked for a simpler way. Laziness as well as exertion can move us forward. It was necessary to think out a method that led to the result by an easier journey. It was necessary to obtain a simple asymptotic result, to obtain it by a simple method, on the fingers, and then it would have been easier to form at once a notion of how it happens"[2].

This criticism might well be viewed as somewhat naïve (or is there a suggestion of a smile behind it?): to construct a simple and adequate model of the phenomenon under study, it would be necessary to have the rare talent with which Frenkel' himself was so generously endowed.

We also find the same reproach for unjustified mathematization, which only creates the illusion of forward motion on the path toward construction of theory, in Frenkel's later utterances. Thus, he wrote in his Preface to the Second Edition of his "Introduction to the Theory of Metals," that physicists "... often diligently develop a theory in its formal mathematical aspect with little interest in the question as to the extent to which its foundations reflect reality. For example, they regard the problem of electron motion in the periodic force field of a crystal as mathematically interesting and beautiful without noticing how schematic and barren are the physical conceptions at its base—conceptions that do not take account of the interaction of the electrons with one another"[8]. In his notes for one of his speeches, he wrote: "Whenever the physical essence of a problem is unclear, mathematics should not be consulted for the guideline to its clarification. It would seem to me much more useful to have a study that helps clarify the essence of the matter—the factors of importance for correct understanding of the phenomenon in which we are interested or, conversely, those that are nonessential to it—in a word, to have a qualitative analysis of the physical problem, than attempts to solve it quantitatively when our information on the essence of the phenomena studied is patently inadequate." (We take note of a somewhat contradictory opinion on this question that was put forward, if epigramatically, by Max Born: "First start the calculations, and then think;" but it was also said seriously and with reason of Born that "Mathematics was always the via regia9) that he traveled to unlock the mysteries of nature"[18].

Fermi's colleagues usually recall him with a slide rule in his hands; he never went out without it[19]. Frenkel' never owned a slide rule—either at work or at home. Nor were there any books of reference tables in his modest home library. Here the parallel to Fermi reemerges: Fermi liked to bet that he could derive and solve the equation describing a process before his colleagues could find the answer in the handbooks. Frenkel' proceeded in the same way, if without the wagering.

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In his appearances in print, in his public lectures, and in his private conversations, Frenkel' paid more than lip service to the idea of including science in the collective notion of the popular cultural level, in the "intellectual minimum" that was limited only to literature and the arts during the 1920's and 1930's. Speaking before the Leningrad writers in 1936, he observed that: "The writer is a victim of the old attitude toward the natural sciences. It was assumed that a man who had completed legal or philosophical studies was universally educated, and that a natural-sciences or physico-mathematical faculty produced only narrow specialization... When we speak of scientific subject matter in literature, we must speak of expanding the horizons of the writers themselves."[2]

It is helpful to recall this now that scientific creativity has been generally recognized as being of the same nature as any other form of creative activity. This unity is based on understanding of the role that imagination and invention play in the birth and development of truly novel ideas and investigations in science and engineering.

From our standpoint, Frenkel's printed papers are also evidence in favor of this unity. First of all, their basic content reflects and embodies his high creative potential. Their language, vivid and picturesque, marks Frenkel' as a man with an unmistakable literary gift. The latter came through most clearly in his letters, some of which have been published, but it was no doubt also manifested in his lyric and humerous verse.

But Frenkel' the artist is seen at his best in these publications. His portraits of his friends and colleagues, landscapes, and pencil sketches were often publicly exhibited and were reproduced in various editions[2,3,20,21]. A student of Ya. N. Kruger, the popular Belorussian artist (who was, in turn, a student of V. E. Makovskiĭ), Frenkel' painted in the classical Russian tradition of the turn of the century. But in his scientific creative activity (and equally in expounding his results), he was, as was aptly observed by Ya. A. Smorodinskiĭ, more of an impressionist painter. Many of his theories were spread over the canvas in bright colors with a broad brush. Training and imagination were needed to appreciate their orderliness and internal logic. Given these, what was apparently a chaos of paints and colored blotches would transform itself into a harmonic whole. For many people, this style of Frenkel's works had the same effect as that of an impressionist painting—the latter would begin to "play" when the viewer had retreated a few steps; Frenkel's theories received the attention and respect that they deserved only after a certain delay (speaking figuratively, when viewed from a few steps (years) away in time).

Frenkel' was also known as a musically gifted man among his close friends and co-workers. He had an excellent musical memory and could whistle major symphonic and chamber works note for note. And, as was characteristic for his nature, his interest in music was active: though no virtuoso, he played the violin with feeling, keeping it with him on extended tours of duty away from home and even during his summer vacations. It is interesting to conjecture whether this side of his intellectual activity was not also reflected in Frenkel's scientific publications.

We cite here yet another example of such indirect reflection that relates to the work that Frenkel' did during the war. From the very outbreak of hostilities, Frenkel' strove to do his part in the national struggle against the Hitlerite barbarians. The Leningrad air defense service asked him to investigate the causes of the streetcar-trolley sparking that was breaking the blackout of the city during the early months of the war. On July and August evenings during 1941, Frenkel' would get on the streetcar at the Polytechnic Institute and try to figure out why the trolley would break away from the wire, to the accompaniment of a bright flash and a shower of sparks. He used the results of his observations to resolve the technical problem and make the corresponding calculations. In a paper published in the Zhurnal Tekhnicheskoĭ Fiziki[22] under the title "Streetcar sparking and its prevention," he reported the results of this study and advanced recommendations for prevention of the sparking. Quite characteristically, Frenkel's picturesque manner of expression came to the fore even in his report on this to all appearances prosaic subject, which was, moreover, written during the difficult months of 1942. Discussing the peculiarities of friction of the trolley against the wire, he writes: "Having a negative characteristic, i.e., decreasing with increasing speed, the frictional force sets up elastic vibrations of the trolley, and also of its upper part, in exactly the same way as a bow sets a string or tuning fork in vibration. Here the wire plays the part of the bow and the stirrup that of the string (tuning fork)." And he goes on to clarify: "Since this phenomenon depends on the relative motion of the trolley and the wire, the trolley (more precisely, the streetcar to which it is attached) can be regarded as stationary and the wire as sliding past it in exactly the same way as the bow slides over the string."

We might conclude this article on Frenkel's scientific creative style with an analysis of the degree to which his basic profession, that of a theoretical physicist, left its impression on the style and language of his letters, on his perception of surrounding nature. He liked to look for the physical secrets behind phenomena ranging from postcard sunsets at sea to the play of a garden fountain, from ramblings about the palette of Rembrandt's later canvases to a discussion of the prospects and foundations of the new synthetic music. His response to what he saw and heard was always quick and direct, his comments witty, and, it would appear, memorable. Unfortunately, as often happens in a close association, what is left of them is a general impression that cannot be tied down to specific details... But here is an episode that engraved itself into the memory of Yu. R. Sokolov, a prewar student of Frenkel' at the Polytechnic Institute. During the light summer nights, he would stroll around Leningrad; the jasmine was in bloom and Frenkel' said: "The fragrance of jasmine is pleasant, but very ordinary and naïve. It is somehow like an unfinished melody."

We end our notes with this poetic and precise comparison.

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[1] Ces choses sont hors de l'homme, le style est de l'homme même.

[2] This last probably has reference to the existence of traditional subjects (for example, biblical subjects in painting, the Eighteenth Century picaresque novel, etc.).

[3] We note in passing that Frenkel' figuratively treats the transition of an atom from a lattice site into an interstice as "internal evaporation."

[4] Private communication. The paper cited by Pekar, "Absorption of Light and Trapping of Electrons and Positive Holes in Crystalline Dielectrics," was published in ZhETF 6, 647 (1936) and in Frenkel's "Sobranie izbrannykh trudov" (Selected Works), Vol. II, Izd-vo Akad. Nauk SSSR, Moscow-Leningrad, 1958 (the quotation was taken from p. 190 of the book).

[5] In 1928, Frenkel' had used a temperature concept to describe the behavior of a molecule.

[6] The two papers, Sommerfeld's and Frenkel's, on the quantum theory of metals were read simultaneously at the 1927 congress at Lake Como.

[7] Private communication.

[8] Of 30 articles published in 1938-1939, eight were included in the volume of Frenkel's selected works (we note that the total number of papers chosen by the editors of that volume was 35).

[9] Royal Road (Lat.).

[1] H. Kramers, in book: P. Ehrenfest, Relativity, Statistics, Quanta. Russ. Transl., Nauka, Moscow, 1972, p. 249.

[2] V. Ya. Frenkel', Yakov Il'ich Frenkel', Nauka, Moscow-Leningrad, 1966.

[3] Ya. I. Frenkel', Na zare novoĭ fizike (At the Dawn of the New Physics), Nauka, Leningrad, 1970.

[4] C. T. Walker and G. A. Slack, Am. J. Phys. 38, 1380 (1970).

[5] L. V. Groshev, Usp. Fiz. Nauk 14, 808 (1934).

[6] V. S. Vavilov, Usp. Fiz. Nauk 84, 431 (1964) [Sov. Phys.-Uspekhi 7, 797 (1965)].

[7] Ya. I. Frenkel', Usp. Fiz. Nauk 16, 955 (1936).

[8] Ya. I. Frenkel', Vvedenie v teoriyu metallov (Introduction to the Theory of Metals), Fourth Edition, Nauka, Leningrad, 1972.

[9] Ya. I. Frenkel', Zh. Tekh. Fiz. 22, 1887 (1952).

[10] Ya. I. Frenkel', Teoriya yavleniĭ atmosfernogo électrichestva (Theory of Atmospheric Electrical Phenomena), Gostekhizdat, Leningrad-Moscow, 1949.

[11] Ya. E. Geguzin, Priroda, No. 3, 113 (1971).

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[13] Ya. I. Frenkel', Volnovaya mekhanika (Wave Mechanics), Part 1, GTTI, Leningrad-Moscow, 1933.

[14] I. E. Tamm, Ya. A. Smorodinskiĭ, in book: Ya. I. Frenkel', Sobranie izbrannykh trudov (Selected Works), Vol. II, Moscow-Leningrad, Izd-vo Akad. Nauk SSSR, 1958, pp. 455.

[15] V. Ya. Frenkel' (ed.), Erenfest-Ioffe, Nauchnaya perepiska (Ehrenfest-Ioffe Scientific Correspondence), Nauka, Leningrad, 1973.

[16] Exploring the History of Nuclear Physics (Proc. of AIP Conference No. 7), Ed. Ch. Weiner, N.Y., 1972.

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[18] Yu. B. Rumer, Usp. Fiz. Nauk 78, 695 (1962).

[19] B. Pontecorvo and V. Pokrovskiĭ, Enriko Fermi (Enrico Fermi), Nauka, Moscow, 1972.

[20] V. Ya. Frenkel', Nauka i Zhizn', No. 4, 80 (1972).

[21] L. I. Kokin, Molodost' akademikov (The Youth of the Academicians), Prosveshchenie, Moscow, 1970.

[22] Ya. I. Frenkel', Zh. Tekh. Fiz. 12, 171 (1942).

Translated by R. W. Bowers