Mechanics

Third Edition

Course of Theoretical Physics
Volume 1

L. D. Landau and E. M. Lifshitz

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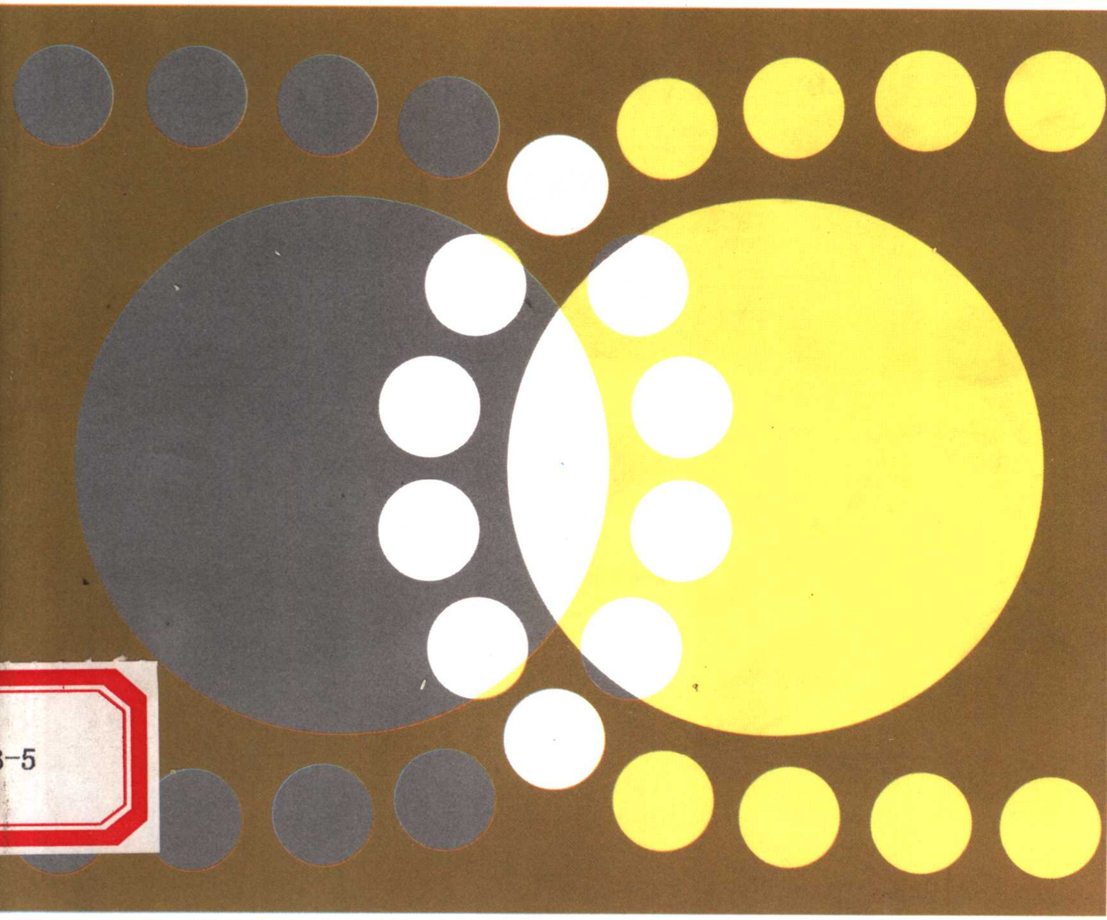

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MECHANIC _

THIRD EDITION

by

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Volume 1 of *Course of Theoretical Physics*

Translated from the Russian by
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PREFACE TO THE THIRD ENGLISH EDITION

THIS book continues the series of English translations of the revised and augmented volumes in the *Course of Theoretical Physics*, which have been appearing in Russian since 1973. The English translations of volumes 2 (*Classical Theory of Fields*) and 3 (*Quantum Mechanics*) will shortly both have been published. Unlike those two, the present volume 1 has not required any considerable revision, as is to be expected in such a well-established branch of theoretical physics as mechanics is. Only the final sections, on adiabatic invariants, have been revised by L. P. Pitaevskiĭ and myself.

The *Course of Theoretical Physics* was initiated by Landau, my teacher and friend. Our work together on these books began in the late 1930s and continued until the tragic accident that befell him in 1962. Landau's work in science was always such as to display his striving for clarity, his effort to make simple what was complex and so to reveal the laws of nature in their true simplicity and beauty. It was this aim which he sought to instil into his pupils, and which has determined the character of the *Course*. I have tried to maintain this spirit, so far as I was able, in the revisions that have had to be made without Landau's participation. It has been my good fortune to find a colleague for this work in L. P. Pitaevskiĭ, a younger pupil of Landau's.

The present edition contains the biography of Landau which I wrote in 1969 for the posthumous Russian edition of his *Collected Works*. I should like to hope that it will give the reader some slight idea of the personality of that remarkable man.

The English translations of the *Course* were begun by Professor M. Hamermesh in 1951 and continued by Dr. J. B. Sykes and his colleagues. No praise can be too great for their attentive and careful work, which has contributed so much to the success of our books in the English-speaking world.

E. M. LIFSHITZ

Institute of Physical Problems
U.S.S.R. Academy of Sciences
Moscow 1976

LEV DAVIDOVICH LANDAU (1908–1968)†

VERY little time has passed since the death of Lev Davidovich Landau on 1 April 1968, but fate wills that even now we view him at a distance, as it were. From that distance we perceive more clearly not only his greatness as a scientist, the significance of whose work becomes increasingly obvious with time, but also that he was a great-hearted human being. He was uncommonly just and benevolent. There is no doubt that therein lie the roots of his popularity as a scientist and teacher, the roots of that genuine love and esteem which his direct and indirect pupils felt for him and which were manifested with such exceptional strength during the days of the struggle to save his life following the terrible accident.

To him fell the tragic fate of dying twice. The first time it happened was six years earlier on 7 January 1962 when on the icy road, en route from Moscow to Dubna, his car skidded and collided with a lorry coming from the opposite direction. The epic story of the subsequent struggle to save his life is primarily a story of the selfless labour and skill of numerous physicians and nurses. But it is also a story of a remarkable feat of solidarity. The calamitous accident agitated the entire community of physicists, arousing a spontaneous and instant response. The hospital in which Landau lay unconscious became a centre to all those – his students and colleagues – who strove to make whatever contributions they could to help the physicians in their desperate struggle to save Landau's life.

"Their feat of comradeship commenced on the very first day. Illustrious scientists who, however, had no idea of medicine, academicians, corresponding members of the scientific academies, doctors, candidates, men of the same generation as the 54-year-old Landau as well as his pupils and *their* still more youthful pupils – all volunteered to act as messengers, chauffeurs, intermediaries, suppliers, secretaries, members of the watch and, lastly, porters and labourers. Their spontaneously established headquarters was located in the office of the Physician-in-Chief of Hospital No. 50 and it became a round-the-clock organizational centre for an unconditional and immediate implementation of any instruction of the attending physicians.

† By E. M. Lifshitz; written for the Russian edition of Landau's *Collected Papers*, and first published in Russian in *Uspekhi fizicheskikh nauk* **97**, 169–183, 1969. This translation is by E. Bergman (first published in *Soviet Physics Uspekhi* **12**, 135–143, 1969), with minor modifications, and is reprinted by kind permission of the American Institute of Physics. The reference numbers correspond to the numbering in the *Collected Papers of L. D. Landau* (Pergamon Press, Oxford 1965).

"Eighty-seven theoreticians and experimenters took part in this voluntary rescue team. An alphabetical list of the telephone numbers and addresses of any one and any institution with which contact might be needed at any instant was compiled, and it contained 223 telephone numbers! It included other hospitals, motor transport bases, airports, customs offices, pharmacies, ministries, and the places at which consulting physicians could most likely be reached.

"During the most tragic days when it seemed that 'Dau is dying' – and there were at least four such days – 8–10 cars could be found waiting at any time in front of the seven-storey hospital building. . . .

"When everything depended on the artificial respiration machine, on 12 January, a theoretician suggested that it should be immediately constructed in the workshops of the Institute of Physical Problems. This was unnecessary and naive, but how amazingly spontaneous! The physicists obtained the machine from the Institute for the Study of Poliomyelitis and carried it in their own hands to the ward where Landau was gasping for breath. They saved their colleague, teacher, and friend.

"The story could be continued without limit. This was a real fraternity of physicists. . . ."†

And so, Landau's life was saved. But when after three months he regained consciousness, it was no longer the same man whom we had known. He was not able to recover from all the consequences of his accident and never again completely regained his abilities. The story of the six years that followed is only a story of prolonged suffering and pain.

* * *

Lev Davidovich Landau was born on 22 January 1908 in Baku, in the family of a petroleum engineer who worked on the Baku oil-fields. His mother was a physician and at one time had engaged in scientific work on physiology.

He completed his school course at the age of 13. Even then he already was attracted by the exact sciences, and his mathematical ability manifested itself very early. He studied mathematical analysis on his own and later he used to say that he hardly remembered a time when he did not know differentiation and integration.

His parents considered him too young to enter a university and for a year he attended the Baku Economic Technicum. In 1922 he enrolled at Baku University where he studied simultaneously in two departments: Physico-mathematical and Chemical. Subsequently he did not continue his chemical education but he remained interested in chemistry throughout his life.

In 1924 Landau transferred to the Physics Department of Leningrad

† From D. Danin, "Comradeship", *Literaturnaya Gazeta* (*Literary Gazette*), 21 July 1962.

University. In Leningrad, the main centre of Soviet physics at that time, he first made the acquaintance of genuine theoretical physics, which was then going through a turbulent period. He devoted himself to its study with all his youthful zeal and enthusiasm and worked so strenuously that often he became so exhausted that at night he could not sleep, still turning over formulae in his mind.

Later he used to describe how at that time he was amazed by the incredible beauty of the general theory of relativity (sometimes he even would declare that such a rapture on first making one's acquaintance with this theory should be a characteristic of any born theoretical physicist). He also described the state of ecstasy to which he was brought on reading the articles by Heisenberg and Schrödinger signalling the birth of the new quantum mechanics. He said that he derived from them not only delight in the true glamour of science but also an acute realization of the power of the human genius, whose greatest triumph is that man is capable of apprehending things beyond the pale of his imagination. And of course, the curvature of space-time and the uncertainty principle are precisely of this kind.

In 1927 Landau graduated from the university and enrolled for post-graduate study at the Leningrad Physicotechnical Institute where even earlier, in 1926, he had been a part-time research student. These years brought his first scientific publications. In 1926 he published a theory of intensities in the spectra of diatomic molecules [1],† and as early as 1927, a study of the problem of damping in quantum mechanics, which first introduced a description of the state of a system with the aid of the density matrix.

His fascination with physics and his first achievements as a scientist were, however, at the time beclouded by a painful diffidence in his relations with others. This trait caused him a great deal of suffering and at times – as he himself confessed in later years – led him to despair. The changes which occurred in him with the years and transformed him into a buoyant and gregarious individual were largely a result of his characteristic self-discipline and feeling of duty toward himself. These qualities, together with his sober and self-critical mind, enabled him to train himself and to evolve into a person with a rare ability – the ability to be happy. The same sobriety of mind enabled him always to distinguish between what is of real value in life and what is unimportant triviality, and thus also to retain his mental equilibrium during the difficult moments which occurred in his life too.

In 1929, on an assignment from the People's Commissariat of Education, Landau travelled abroad and for one and a half years worked in Denmark, Great Britain and Switzerland. To him the most important part of his trip was his stay in Copenhagen where, at the Institute of Theoretical Physics,

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† He did not know, however, at the time that these results had been already published a year earlier by Hönl and London.

theoretical physicists from all Europe gathered round the great Niels Bohr and, during the famous seminars headed by Bohr, discussed all the basic problems of the theoretical physics of the time. This scientific atmosphere, enhanced by the charm of the personality of Bohr himself, decisively influenced Landau in forming his own outlook on physics and subsequently he always considered himself a disciple of Niels Bohr. He visited Copenhagen two more times, in 1933 and 1934. Landau's sojourn abroad was the occasion, in particular, of his work on the theory of the diamagnetism of an electron gas [4] and the study of the limitations imposed on the measurability of physical quantities in the relativistic quantum region (in collaboration with Peierls) [6].

On his return to Leningrad in 1931 Landau worked in the Leningrad Physicotechnical Institute and in 1932 he moved to Khar'kov, where he became head of the Theoretical Division of the newly organized Ukrainian Physicotechnical Institute, an offshoot of the Leningrad Institute. At the same time he headed the Department of Theoretical Physics at the Physics and Mechanics Faculty of the Khar'kov Mechanics and Machine Building Institute and in 1935 he became Professor of General Physics at Khar'kov University.

The Khar'kov period was for Landau a time of intense and varied research activity.† It was there that he began his teaching career and established his own school of theoretical physics.

Twentieth-century theoretical physics is rich in illustrious names of trail-blazing creators, and Landau was one of these creators. But his influence on scientific progress was far from exhausted by his personal contribution to it. He was not only an outstanding physicist but also a genuinely outstanding educator, a born educator. In this respect one may take the liberty of comparing Landau only to his own teacher – Niels Bohr.

The problems of the teaching of theoretical physics as well as of physics as a whole had first attracted his interest while still quite a young man. It was there, in Khar'kov, that he first began to work out programmes for the "theoretical minimum" – programmes of the basic knowledge in theoretical physics needed by experimental physicists and by those who wish to devote themselves to professional research work in theoretical physics. In addition to drafting these programmes, he gave lectures on theoretical physics to the scientific staff at the Ukrainian Physicotechnical Institute as well as to students of the Physics and Mechanics Faculty. Attracted by the ideas of reorganizing instruction in physics as a whole, he accepted the Chair of General Physics at Khar'kov State University (and subsequently, after

† The extent of Landau's scientific activities at the time can be grasped from the list of studies he completed during the year 1936 alone: theory of second-order phase transitions [29], theory of the intermediate state of superconductors [30], the transport equation in the case of Coulomb interaction [24], the theory of unimolecular reactions [23], properties of metals at very low temperatures [25], theory of the dispersion and absorption of sound [22, 28], theory of photoelectric effects in semiconductors [21].

the war, he continued to give lectures on general physics at the Physico-technical Faculty of Moscow State University).

It was there also, in Khar'kov, that Landau had conceived the idea and began to implement the programme for compiling a complete Course of Theoretical Physics and Course of General Physics. All his life long, Landau dreamed of writing books on physics at every level – from school textbooks to a course of theoretical physics for specialists. In fact, by the time of his fateful accident, nearly all the volumes of the *Course of Theoretical Physics* and the first volumes of the *Course of General Physics* and *Physics for Everyone* had been completed. He also had drafted plans for the compilation of textbooks on mathematics for physicists, which should be "a guide to action", should instruct in the practical applications of mathematics to physics, and should be free of the rigours and complexities unnecessary to this course. He did not have time to begin to translate this programme into reality.

Landau always attached great importance to the mastering of mathematical techniques by the theoretical physicist. The degree of this mastery should be such that, insofar as possible, mathematical complications would not distract attention from the physical difficulties of the problem – at least whenever standard mathematical techniques are concerned. This can be achieved only by sufficient training. Yet experience shows that the current style and programmes for university instruction in mathematics for physicists often do not ensure such training. Experience also shows that after a physicist commences his independent research activity he finds the study of mathematics too "boring".

Therefore, the first test which Landau gave to anyone who desired to become one of his students was a quiz in mathematics in its "practical" calculational aspects.† The successful applicant could then pass on to the study of the seven successive sections of the programme for the "theoretical minimum", which includes basic knowledge of all the domains of theoretical physics, and subsequently take an appropriate examination. In Landau's opinion, this basic knowledge should be mastered by any theoretician regardless of his future specialization. Of course, he did not expect anyone to be as universally well-versed in science as he himself. But he thus manifested his belief in the integrity of theoretical physics as a single science with unified methods.

At first Landau himself gave the examination for the "theoretical minimum". Subsequently, after the number of applicants became too large, this duty was shared with his closest associates. But Landau always re-

† The requirements were: ability to evaluate any indefinite integral that can be expressed in terms of elementary functions and to solve any ordinary differential equation of the standard type, knowledge of vector analysis and tensor algebra as well as of the principles of the theory of functions of a complex variable (theory of residues, Laplace method). It was assumed that such fields as tensor analysis and group theory would be studied together with the fields of theoretical physics to which they apply.

served for himself the first test, the first meeting with each new young applicant. Anyone could meet him – it was sufficient to ring him up and ask him for an interview.

Of course, not every one who began to study the "theoretical minimum" had sufficient ability and persistence to complete it. Altogether, between 1934 and 1961, 43 persons passed this test. The effectiveness of this selection can be perceived from the following indicative facts alone: of these persons 7 already have become members of the Academy of Sciences and an additional 16, doctors of sciences.

In the spring of 1937 Landau moved to Moscow where he became head of the Theoretical Division of the Institute of Physical Problems which had not long before been established under the direction of P. L. Kapitza. There he remained to the end of his life; in this Institute, which became a home to him, his varied activity reached its full flowering. It was there, in a remarkable interaction with experimental research, that Landau created what may be the outstanding accomplishment of his scientific life – the theory of quantum fluids.

It was there also that he received the numerous outward manifestations of the recognition of his contributions. In 1946 he was elected a full Member of the USSR Academy of Sciences. He was awarded a number of orders (including two Orders of Lenin) and the honorific title of Hero of Socialist Labour – a reward for both his scientific accomplishments and his contribution to the implementation of important practical State tasks. He was awarded the State Prize three times and in 1962, the Lenin Prize. There also was no lack of honorific awards from other countries. As far back as 1951 he was elected member of the Danish Royal Academy of Sciences and in 1956, member of the Netherlands Royal Academy of Sciences. In 1959 he became honorary fellow of the British Institute of Physics and Physical Society and in 1960, Foreign Member of the Royal Society of Great Britain. In the same year he was elected to membership in the National Academy of Sciences of the United States and the American Academy of Arts and Sciences. In 1960 he became recipient of the F. London Prize (United States) and of the Max Planck Medal (West Germany). Lastly, in 1962 he was awarded the Nobel Prize in Physics "for his pioneering theories for condensed matter, especially liquid helium".

Landau's scientific influence was, of course, far from confined to his own disciples. He was deeply democratic in his life as a scientist (and in his life as a human being, for that matter; pomposity and deference to titles always remained foreign to him). Anyone, regardless of his scientific merits and title, could ask Landau for counsel and criticism (which were invariably precise and clear), on one condition only: the question must be businesslike instead of pertaining to what he detested most in science: empty philosophizing or vapidity and futility cloaked in pseudo-scientific sophistries. He had an acutely critical mind; this quality, along with his approach from the standpoint of profound physics, made discussion with him extremely attractive and useful.

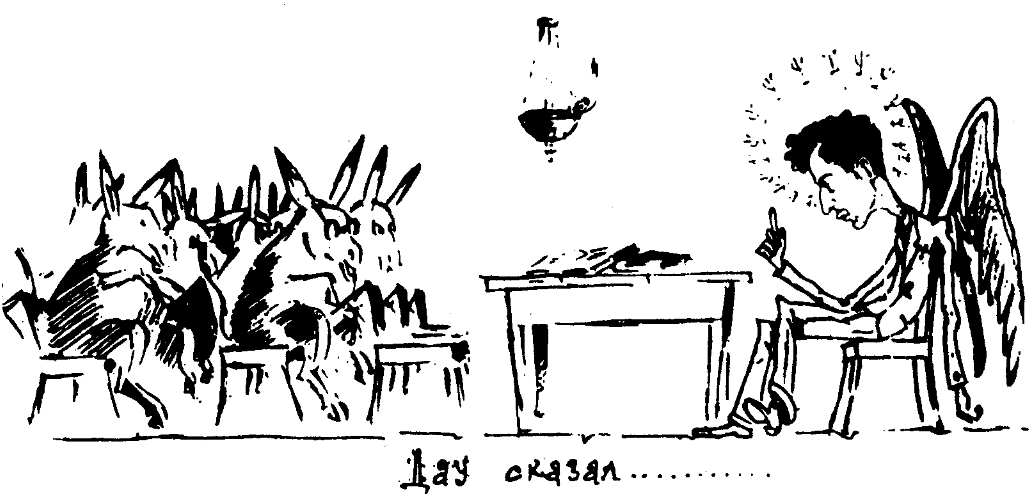
In discussion he used to be ardent and incisive but not rude; witty and ironic but not caustic. The nameplate which he hung on the door of his office at the Ukrainian Physicotechnical Institute bore the inscription:

L. LANDAU
BEWARE, HE BITES!

With years his character and manner mellowed somewhat, but his enthusiasm for science and his uncompromising attitude toward science remained unchanged. And certainly his sharp exterior concealed a scientifically impartial attitude, a great heart and great kindness. However harsh and unsparing he may have been in his critical comments, he was just as intense in his desire to contribute with his advice to another man's success, and his approval, when he gave it, was just as ardent.

These traits of Landau's personality as a scientist and of his talent actually elevated him to the position of a supreme scientific judge, as it were, over his students and colleagues.† There is no doubt that this side of Landau's activities, his scientific and moral authority which exerted a restraining influence on frivolity in research, has also markedly contributed to the lofty level of our theoretical physics.

His constant scientific contact with a large number of students and colleagues also represented to Landau a source of knowledge. A unique aspect of his style of work was that, ever since long ago, since the Khar'kov years, he himself almost never read any scientific article or book but nevertheless he was always completely au courant with the latest news in physics.



† This position is symbolized in A. A. Yuzefovich's well-known friendly cartoon, "Dau said", reproduced here.

He derived this knowledge from numerous discussions and from the papers presented at the seminar held under his direction.

This seminar was held regularly once a week for nearly 30 years, and in the last years its sessions became gatherings of theoretical physicists from all Moscow. The presentation of papers at this seminar became a sacred duty for all students and co-workers, and Landau himself was extremely serious and thorough in selecting the material to be presented. He was interested and equally competent in every aspect of physics and the participants in the seminar did not find it easy to follow his train of thought in instantaneously switching from the discussion of, say, the properties of "strange" particles to the discussion of the energy spectrum of electrons in silicon. To Landau himself listening to the papers was never an empty formality: he did not rest until the essence of a study was completely elucidated and all traces of "philology" – unproved statements or propositions made on the principle of "why might it not" – therein were eliminated. As a result of such discussion and criticism many studies were condemned as "pathology" and Landau completely lost interest in them. On the other hand, articles that really contained new ideas or findings were included in the so-called "gold fund" and remained in Landau's memory for ever.

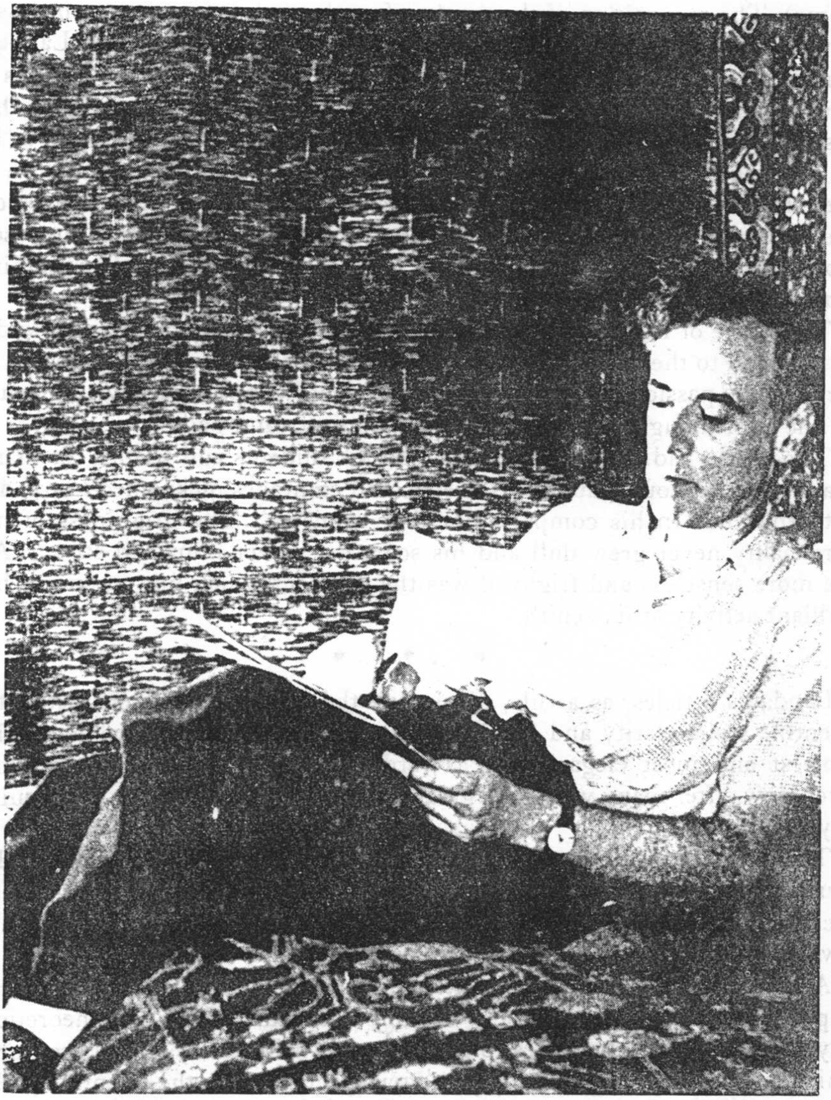
In fact, usually it was sufficient for him to know just the guiding idea of a study in order to reproduce all of its findings. As a rule, he found it easier to obtain them on his own than to follow in detail the author's reasoning. In this way he reproduced for himself and profoundly thought out most of the basic results obtained in all the domains of theoretical physics.† This probably also was the reason for his phenomenal ability to answer practically any question concerning physics that might be asked of him.

Landau's scientific style was free of the – unfortunately fairly widespread – tendency to complicate simple things (often on the grounds of generality and rigour which, however, usually turn out to be illusory). He himself always strove towards the opposite – to simplify complex things, to uncover in the most lucid manner the genuine simplicity of the laws underlying the natural phenomena. This ability of his, this skill at "trivializing" things as he himself used to say, was to him a matter of special pride.

The striving for simplicity and order was an inherent part of the structure of Landau's mind. It manifested itself not only in serious matters but also in semi-serious things as well as in his characteristic personal sense of humour.‡ Thus, he liked to classify everyone, from women according to the degree of their beauty, to theoretical physicists according to the signifi-

† Incidentally, this explains the absence of certain needed references in Landau's papers, which usually was not intentional. However, in some cases he could leave out a reference on purpose, if he considered the question too trivial; and he did have his own rather high standards on that matter.

‡ It is characteristic, however, that this trait was not a habit of Landau in his, so to speak, everyday outside life, in which he was not at all pedantically accurate and a "zone of disorder" would quite rapidly arise around him.



cance of their contribution to science. This last classification was based on a logarithmic scale of five: thus, a second-class physicist supposedly accomplished 10 times as much as a third-class physicist ("pathological types" were ranked in the fifth class). On this scale Einstein occupied the position $\frac{1}{2}$, while Bohr, Heisenberg, Schrödinger, Dirac and certain others were ranked in the first class. Landau modestly ranked himself for a long time in class $2\frac{1}{2}$ and it was only comparatively late in his life that he promoted himself to the second class.

He always worked hard (never at a desk, usually reclining on a divan at home). The recognition of the results of one's work is to a greater or lesser extent important to any scientist; it was, of course, also essential to Landau. But it can still be said that he attached much less importance to questions of priority than is ordinarily the case. And at any rate there is no doubt that his drive for work was inherently motivated not by desire for fame but by an inexhaustible curiosity and passion for exploring the laws of nature in their large and small manifestations. He never omitted a chance to repeat the elementary truth that one should never work for extraneous purposes, work merely for the sake of making a great discovery, for then nothing would be accomplished anyway.

The range of Landau's interests outside physics also was extremely wide. In addition to the exact sciences he loved history and was well-versed in it. He was also passionately interested in and deeply impressed by every genre of fine arts, though with the exception of music (and ballet).

Those who had the good fortune to be his students and friends for many years knew that our Dau, as his friends and comrades nicknamed him†, did not grow old. In his company boredom vanished. The brightness of his personality never grew dull and his scientific power remained strong. All the more senseless and frightful was the accident which put an end to his brilliant activity at its zenith.

* * *

Landau's articles, as a rule, display all the features of his characteristic scientific style: clarity and lucidity of physical statement of problems, the shortest and most elegant path towards their solution, no superfluities. Even now, after many years, the greater part of his articles does not require any revisions.

The brief review below is intended to provide only a tentative idea of the abundance and diversity of Landau's work and to clarify to some extent the place occupied by it in the history of physics, a place which may not always be obvious to the contemporary reader.

A characteristic feature of Landau's scientific creativity is its almost unprecedented breadth, which encompasses the whole of theoretical physics, from hydrodynamics to the quantum field theory. In our century, which is a century of increasingly narrow specialization, the scientific paths of his students also have been gradually diverging, but Landau himself unified them all, always retaining a truly astounding interest in everything. It may be that in him physics has lost one of the last great universalists.

Even a cursory examination of the bibliography of Landau's works shows that his life cannot be divided into any lengthy periods during which he worked only in some one domain of physics. Hence also the survey of his works is given not in chronological order but, insofar as possible, in thematic

† Landau himself liked to say that this name originated from the French spelling of his name: Landau = L'âne Dau (the ass Dau).

order. We shall begin with the works devoted to the general problems of quantum mechanics.

These include, in the first place, several of his early works. In the course of his studies of the radiation-damping problem he was the first to introduce the concept of incomplete quantum-mechanical description accomplished with the aid of quantities which were subsequently termed the density matrix [2]. In this article the density matrix was introduced in its energy representation.

Two articles [7, 9] are devoted to the calculation of the probabilities of quasiclassical processes. The difficulty of this problem stems from the fact that, by virtue of the exponential nature (with a large imaginary exponent) of the quasiclassical wave functions, the integrand in the matrix elements is a rapidly fluctuating quantity; this greatly complicates even an estimate of the integral; in fact, until Landau's work all studies of problems of this kind were erroneous. Landau was the first to provide a general method for the calculation of quasiclassical matrix elements and he also applied it to a number of specific processes.

In 1930 Landau (in collaboration with R. Peierls) published a detailed study of the limitations imposed by relativistic requirements on the quantum-mechanical description [6]; this article caused lively discussions at the time. Its basic result lies in determining the limits of the possibility of measuring the particle momentum within a finite time. This implied that in the relativistic quantum region it is not feasible to measure any dynamical variables characterizing the particles in their interaction, and that the only measurable quantities are the momenta (and polarizations) of free particles. Therein also lies the physical root of the difficulties that arise when methods of conventional quantum mechanics, employing concepts which become meaningless in the relativistic domain, are applied there. Landau returned to this problem in his last published article [100], in which he expressed his conviction that the ψ-operators, as carriers of unobservable information, and along with them the entire Hamiltonian method, should disappear from a future theory.

One of the reasons for this conviction was the results of the research into the foundations of quantum electrodynamics which Landau carried out during 1954–1955 (in collaboration with A. A. Abrikosov, I. M. Khalatnikov and I. Ya. Pomeranchuk) [78-81, 86]. These studies were based on the concept of the point interaction as the limit of "smeared" interaction when the smearing radius tends to zero. This made it possible to deal directly with finite expressions. Further, it proved possible to carry out the summation of the principal terms of the entire series of perturbation theory and this led to the derivation of asymptotic expressions (for the case of large momenta) for the fundamental quantities of quantum electrodynamics – the Green functions and the vertex part. These relations, in their own turn, were used to derive the relationship between the true charge and mass of the electron, on the one hand, and their "bare" values, on the other. Although these calculations proceeded on the premise of smallness of the "bare" charge, it was argued that the formula for the relation between true and bare charges retains its validity regardless of the magnitude of the bare charge. Then analysis of this formula shows that at the limit of point interaction the true charge becomes zero – the theory is "nullified".† (A review of the pertinent questions is provided in the articles [84, 89]).

Only the future will show the extent of the validity of the programme planned by Landau [100] for constructing a relativistic quantum field theory. He himself was energetically working in this direction during the last few years prior to his accident. As part of this programme, in particular, he had worked out a general method for determining the singularities of the quantities that occur in the diagram technique of quantum field theory [98].

In response to the discovery in 1956 of parity nonconservation in weak interactions, Landau immediately proposed the theory of a neutrino with fixed helicity ("two-component neutrino") [92]‡, and also suggested the principle of the conservation of "combined parity", as he termed the combined application of spatial inversion and charge conjugation. According to Landau, the symmetry of space would in this way be "saved" – the asymmetry is transferred to the particles themselves. This principle indeed proved to be more widely applicable than the law of parity conservation. As is known, however, in recent years processes not conserving combined parity have also been discovered; the meaning of this violation is at present still unclear.

A 1937 study [31] by Landau pertains to nuclear physics. This study represents a quantitative embodiment of the ideas proposed not long before by Bohr: the nucleus is examined by methods of statistical physics as a drop of "quantum fluid". It is noteworthy that this study did not make use of any far-reaching model conceptions, contrary to the previous practice of other investigators. In particular, the relationship between the mean distance between the levels of the compound nucleus and the width of the levels was established for the first time.

The absence of model conceptions is characteristic also of the theory of proton–proton scattering developed by Landau (in collaboration with Ya. A. Smorodinskii) [55]. The scattering cross-section in their study was expressed in terms of parameters whose meaning is not restricted by any specific assumptions concerning the particle interaction potential.

The study (in collaboration with Yu. B. Rumer) [36] of the cascade

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† In connection with the search for a more rigorous proof of this statement, the article [100] contains the assertion, characteristic of Landau, that "the brevity of life does not allow us the luxury of spending time on problems which will lead to no new results".

‡ Simultaneously and independently, this theory was proposed by Salam and by Lee and Yang.

theory of electron showers in cosmic rays is an example of technical virtuosity; the physical foundations of this theory had been earlier formulated by a number of investigators, but a quantitative theory was essentially lacking. That study provided the mathematical apparatus which became the basis for all subsequent work in this domain. Landau himself took part in the further refinement of the shower theory by contributing two more articles, one on the particle angular distribution [43] and the other on secondary showers [44].

Of no smaller virtuosity was Landau's work dealing with the elaboration of Fermi's idea of the statistical nature of multiple particle production in collisions [74]. This study also represents a brilliant example of the methodological unity of theoretical physics in which the solution of a problem is accomplished by using the methods from a seemingly completely different domain. Landau showed that the process of multiple production includes the stage of the expansion of a "cloud" whose dimensions are large compared with the mean free path of particles in it; correspondingly, this stage should be described by equations of relativistic hydrodynamics. The solution of these equations required a number of ingenious techniques as well as a thorough analysis. Landau used to say that this study cost him more effort than any other problem that he had ever solved.

Landau always willingly responded to the requests and needs of the experimenters, e.g. by publishing the article [56] which established the energy distribution of the ionization losses of fast particles during passage through matter (previously only the theory of mean energy loss had existed).

Turning now to Landau's work on macroscopic physics, we begin with several articles representing his contribution to the physics of magnetism.

According to classical mechanics and statistics, a change in the pattern of movement of free electrons in a magnetic field cannot result in the appearance of new magnetic properties of the system. Landau was the first to elucidate the character of this motion in a magnetic field for the quantum case, and to show that quantization completely changes the situation, resulting in the appearance of diamagnetism of the free electron gas ("Landau diamagnetism" as this effect is now termed) [4]. The same study qualitatively predicted the periodic dependence of the magnetic susceptibility on the intensity of the magnetic field when this intensity is high. At the time (1930) this phenomenon had not yet been observed by anyone, and it was experimentally discovered only later (the De Haas–Van Alphen effect); a quantitative theory of this effect was presented by Landau in a later paper [38].

A short article published in 1933 [12] is of a significance greatly transcending the problem stated in its title – a possible explanation of the field dependence of the magnetic susceptibility of a particular class of substances