A near-fatal accident 40 years ago robbed theoretical physics of one its greatest minds. Although Lev Landau was never to work again, he was awarded the Nobel prize later that year and his legacy lives on to this day

Lev Landau: physicist and revolutionary

Alexei Kojevnikov

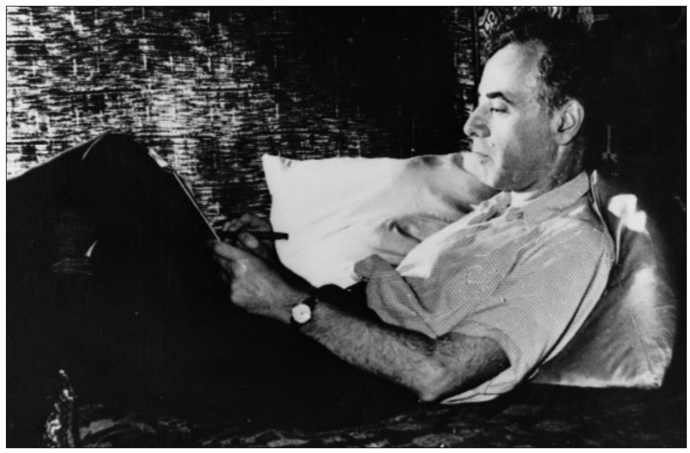
LANDAU requires no introduction. He is too well known, although not quite as well understood. Several generations of theoretical physicists learned their trade by struggling through the 10 volumes of his famous *Course of Theoretical Physics* – known colloquially as Landau and Lifshitz – which Landau supervised, although he did not write a single word. Several dozen physicists – some absolutely first-class – continued to identify themselves as members of the Landau school long after they became scientists in their own right.

About a dozen landmark results in physics bear his name. If one were to choose his most important breakthroughs, these would probably be his theory of phase transitions (1937), the theory of superfluidity in liquid helium (1941), the Ginzburg–Landau phenomenological theory of superconductivity (1950) and the Landau "Fermi-liquid" theory (1956). But his fame is certainly much greater than these concrete results alone might suggest – even if one were to include other formulae, such as the Landau diamagnetism of free electrons (1930) or Landau damping in plasmas (1946). Landau's published papers are so laconic – consisting mainly of formulae and a few categorical statements on what is right and what is wrong, without sufficient explanation – that even professional physicists often found it hard to understand where his ideas came from.

Landau's life and opinions have also been the subject of controversy and confusion. There are many stories and posthumous recollections of him, although very few written documents of the time have survived. Landau neither wrote nor kept letters, and did almost everything he could to complicate the task of future historians. The richest record is probably his KGB file, the bulk of which was released in 1991. One reason for the lack of written sources is that Landau lived in a revolutionary period that was far more turbulent and dangerous than the world of today. Indeed, many aspects of Landau's life appear strange and paradoxical to our contemporary mindset if taken out of the context of his own, very different time.

A quantum rebel

Lev Davidovich Landau belonged to the first truly Soviet generation of scientists educated immediately after the Revolution. He was born in 1908 in Baku, the Transcaucasian oil capital, to the middle-class Jewish family of a petroleum engineer. As a child, Landau was a prodigy and *enfant terrible*, and to some extent he retained childish characteristics well into adult life. By the age of 13 he had learned calculus, contemplated suicide and had almost been expelled from school because of his rebelliousness. It would be hard to imagine Landau doing well in a regular, disciplined system of education. But, luckily for him, the old-fashioned school system was dismantled after the Communists came to power in the Caucasus in 1920.



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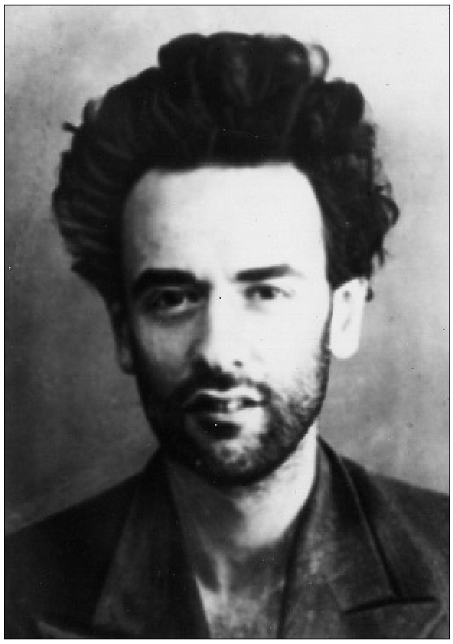
Lev Davidovich Landau (1908–1968) was one of the most influential theoretical physicists of the 20th century, winning the 1962 Nobel Prize for Physics for his pioneering theories of condensed matter.

The new Soviet school was more open, chaotic and subject to all kinds of radical reorganizations and pedagogical experiments. The revolutionary education system did not, for instance, recognize diplomas or academic titles. One could, in principle, go to university without having finished high school, then start a graduate programme without a university diploma, before being hired as a professor without even gaining a PhD. For someone like Landau, the new style was a big advantage. He skipped several formal stages – he never wrote a thesis, for example – but between 1924 and 1927 he did take regular classes at Leningrad University.

It was during these years that the new theory of quantum mechanics arrived from Germany. Landau studied it together with his classmates George Gamow and Dmitry Ivanenko, while the somewhat older Yakov Frenkel and Vladimir Fock began teaching courses on the new physics. Even before he graduated – and without seeking permission or encouragement from professors – the teenage Landau and his friends started writing papers for *Zeitschrift für Physik*. Quantum theory became an integral part of their youth culture, along with social and political radicalism, disrespect towards senior colleagues and a love of poetry and practical jokes.

Amid this youthful rambling, Soviet theoretical physics was born. Domestically, its rise was supported by the Bolsheviks' cultural policies, which at the time were geared towards radical students rather than their more conservative teachers. Internationally, the new discipline matured with the help of Rockefeller fellowships that allowed half-a-dozen young Soviet theorists – the future leaders of the field – to spend time in the main centres of European physics. Landau travelled for more than a year on one such scholarship, visiting Berlin, Leipzig, Cambridge, Zurich and Copenhagen, where he learned, in particular, from Niels Bohr and Wolfgang Pauli. He returned to Leningrad in March 1931, feeling that his task was to establish the discipline of "theoretics" – as he dubbed his profession – in the Soviet Union. In the mind of the 23 year old, the social revolution in his country and the concurrent revolution in physics were two sides of the same coin.



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Landau was jailed in 1938 at the height of the Stalinist purges. He was released a year later thanks to the efforts of his colleague Piotr Kapitza. Landau's KGB file remains the most fertile source of information about his life.

Challenging conventions

The young upstart was a keen critic, and nothing motivated his research more than the possibility of revealing the limitations of existing approaches or exposing somebody's mistakes or oversights. His best known early accomplishment was his demonstration in 1930 that Pauli's "spin paramagnetism" – the alignment of spins in an external magnetic field – is not the only magnetic property of the gas of free electrons in a solid. Landau pointed out that electrons would also display the opposite effect – diamagnetism – resulting from the quantization of their orbits in a magnetic field.

Some of the young radical's other proposals, however, went a little too far even for the condescending authorities. With the enthusiasm of converts, he and Rudolf Peierls applied Bohr's complementarity argument to relativistic quantum electrodynamics. They argued that the infinities and negative-energy solutions, which were regarded at the time as the theory's fatal difficulties, resulted from uncertainty limitations on measurement that were much more severe than those that – according to Bohr – existed in non-relativistic quantum theory.

Landau and Peierls were by no means alone in considering quantum electrodynamics to be in crisis. But in Bohr's view, their call for a new revolution in fundamental physical concepts chose the wrong target – the classical electromagnetic field – as the main source of problems. In addition, Landau was probably unaware that in Copenhagen, unlike the revolutionary Soviet Union, academic hierarchy was still respected. High-level debate about the philosophical fundamentals of quantum theory was the privilege of Bohr and a few recognized masters, not apprentices in the field.

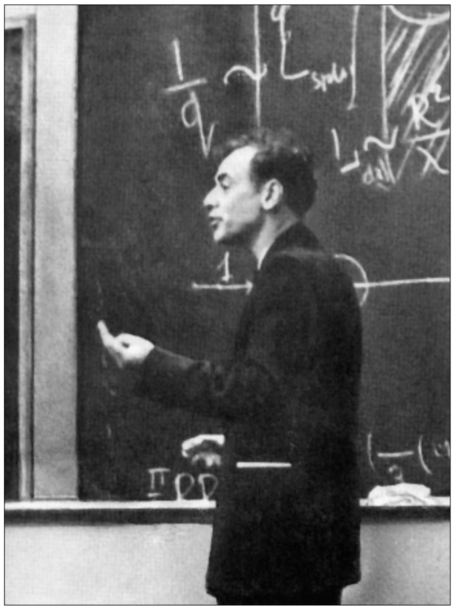
It took Bohr and Léon Rosenfeld three years to write a response that in 1933 validated the notion of the electromagnetic field in relativistic quantum theory and persuaded most physicists. Although Landau remained unconvinced, he kept silent and eventually redirected his main efforts from the foundations of quantum physics towards its applications. Before that happened, in another paper of 1932 he suggested that the laws of quantum physics and the conservation of energy break down deep inside stars due to the high density and temperature. Bohr, too, had entertained the idea of the non-conservation of energy, but Landau's proposal troubled some Marxist philosophers back home, who thought it bordered on idealism.

Back in Leningrad, Landau also ridiculed Abram Joffe, the doyen of Soviet physics and the man who had masterminded its institutional expansion. Joffe, Landau argued, had not sufficiently mastered the latest theories in physics. Landau's behaviour towards his institute's boss was rude, but his judgement – as far as the physics was concerned – was correct. Joffe's well publicized project on making highly efficient insulators using thin films was theoretically misconceived and, as later investigations showed, was also based on some inaccurate preliminary measurements. Unlike Landau, Joffe was an old-fashionably polite, mild-mannered man, who subscribed to a more traditional view on the role of theory in physics. In 1932 he and other senior experimentalists blocked an attempt by the impudent gang of young theorists to secure an entirely separate institute for themselves.

After that disappointment, Landau moved from Leningrad to Kharkov – some 400 km east of Kiev – where the directors of the newest and more modernist Ukrainian Physico-Technical Institute wanted to establish a significant group of theorists. Although their hopes of luring someone more senior like Paul Ehrenfest failed to materialize, Landau had, within a few years, become the leading theorist in Kharkov.

The Kharkov period

In Kharkov, Landau attracted a group of talented graduate students, including Aleksandr Kompaneets, Evgeny Lifshitz, Isaak Pomeranchuk and Aleksandr Akhiezer. He did not encourage them to become rebels – like the one he had been – but to acquire technical skills and calculate real effects. The times were also changing, and the enthusiasm of the cultural revolution began to give way to a renewed emphasis on solid training and disciplined expertise. From 1934 onwards Soviet graduate students were once again required to write theses and to earn degrees equivalent to PhDs. Landau, too, became more reserved and thorough in his papers, although hardly more polite in behaviour. He and his students calculated various effects in quantum electrodynamics – on stopping, pair creation and the scattering of light on light – but their attention was increasingly turning towards the solid state.



Landau at a seminar in the 1950s. His conceptual innovations became the standard language of many-body and condensed-matter physics.

In 1934, under the leadership of Lev Shubnikov, Kharkov became the first Soviet laboratory to liquefy helium and to develop a thriving experimental research programme on superconductivity and other low-temperature effects in metals. Landau's close collaboration with experimentalists helped him to predict in 1933 the phenomenon of "antiferromagnetism" – the possibility that neighbouring magnetic moments point in opposite directions in some solids.

He also attempted to attack the riddle of superconductivity – the flow of current without resistance. Landau used the hypothesis of local "saturation currents" that become ordered under certain conditions, just as the magnetic moments in the domains in a ferromagnet align when a magnetic field is applied. That microscopic model did not work, but Landau later succeeded with a more phenomenological approach. In 1937 he developed a satisfactory theory of the "intermediate" state, describing the behaviour of a superconductor in a magnetic field below the critical value at which the superconducting state disappears. In Landau's model, the state consisted of alternating layers of superconducting and normal phases. Much later, in 1950, he and Vitaly Ginzburg formulated the correct set of macroscopic equations for superconductivity.

Landau's crowning achievement during his period at Kharkov was his theory of "second-order" phase transitions, in which the state of a system – such as its energy – changes continuously, but its symmetry switches. Landau's primary motivation was to describe the transition from liquid to solid, but his thermodynamic theory was extremely general in nature and subsequently found a wide spectrum of applications. He developed it while still at Kharkov, but by the time the paper was published in 1937, Landau had already made his own abrupt transition to Moscow.

Escape to Moscow

Landau's departure from Kharkov illustrates the surreal nature of Stalinist society. The story begins in December 1936, when Landau had a personal quarrel with the rector of Kharkov University, where he was teaching part time. Emerging from the meeting, Landau announced that he was about to be fired. In an attempt to put pressure on the administration, seven of his colleagues and students, including Shubnikov, resigned from their part-time teaching posts. A month later, however, this minor incident became life-threatening. The waves of political purges against the Trotskyites that were rolling across the country reached the university, and a number of university officials, including the rector, disappeared forever.

Amid the poisonous atmosphere, which saw much soul-searching, finger-pointing and a paranoid vigilance against "enemies from within", speakers at a public meeting in Kharkov denounced the act of collective resignation as a strike against the Soviet system. Whether Landau was simply terrified or just grasped intuitively that a quick change of location might boost his chances of survival, he also suddenly disappeared. Several weeks later his friends at Kharkov received a message that he had moved to Moscow, where he had taken a job at the new Institute of Physical Problems under the directorship of Piotr Kapitza.

Kapitza had previously been director of the Mond laboratory in Cambridge, which was sited next to the famous Cavendish Laboratory. In 1934, however, the Soviet government decided that it was no longer acceptable for Kapitza to work abroad and refused to let him return to Britain. Undeterred, by 1937 he had built a new institute in Moscow, equipped with copies of his Cambridge instruments, and was ready to resume his research into magnetism and low-temperature phenomena.

In Landau, Kapitza found a much-needed in-house theorist, and the difficult year 1937 marked the start of a great period of scientific successes for them both. In February Kapitza liquefied helium, and by the end of the year was able to report a major discovery – the new phenomenon of superfluidity. Kapitza found that at temperatures below 2.18 K helium flows through narrow capillaries without any measurable friction. Further experiments revealed additional details of the superfluid's strange behaviour that cried out for an explanation. Landau went on to develop a theory of superfluidity in 1941 – and it was thanks to Kapitza that he had the opportunity.

Six months after Landau ran for his life from Kharkov, the chaotic machine of the purges picked the Ukrainian Physico-Technical Institute for its deadly carnage. Several top scientists including Shubnikov were arrested, forced to confess the crimes of "espionage" and "sabotage", and, after a short trial, executed. Landau's name figured in some of the extorted confessions, but the fact that he was in another city delayed his arrest for at least another six months. Landau, however, came under surveillance and was imprisoned on 28 April 1938 together with two friends and colleagues.

The incriminating evidence was a May Day leaflet written by one of them in the name of an imaginary "Moscow committee of the anti-fascist workers' party", calling on comrades to "save socialism from the criminal Stalinist clique". Although some of Landau's students still remain unconvinced by the authenticity of the document, the leaflet was probably genuine and Landau appears to have dictated or at least approved it. Still, he was somewhat lucky even in this grave misfortune, for by 1938 the purges had already begun to subside, while investigations and trials had become less expedite. This turn of events gave Kapitza time to rescue Landau from prison.

Forced to remain in the Soviet Union, Kapitza began consciously building up connections and using occasional opportunities to write to high-ranking politicians about his work and problems. In Landau's case, Kapitza acted immediately

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A strong group grew up around Landau during his years in the theoretical division of the Institute of Physical Problems in Moscow, where he worked from 1937 until his near-fatal car accident in 1962. Landau is shown here at the institute in 1956 with his colleague Evgenii Lifshitz, with whom Landau wrote the famous *Course of Theoretical Physics*. Back row (left to right): S S Gershtein, L P Pitaevskii, L A Vainshtein, R G Arkhipov, I E Dzyaloshinskii. Front row (left to right) L A Prozorova, A A Abrikosov, I M Khalatnikov, L D Landau, E M Lifshitz.

by sending a personal letter to Stalin. A year later, having received no response and no news, Kapitza wrote to prime minister Vyacheslav Molotov, claiming that he needed Landau's help to understand his recent discoveries in helium. This time the letter worked. Kapitza was allowed to bail the convicted prisoner out of jail in return for a written promise to prevent Landau from committing further "counter-revolutionary" acts. If Landau, who had become quite fragile, had remained in jail it is unlikely he would have survived the physical hardships of prison life.

Collective excitations

While Landau was in prison, Laszlo Tisza in Paris was developing a theory in which atoms of liquid helium were divided into a normal and a superfluid fraction. In Landau's view, however, this "two-fluid" theory mistakenly assumed that the superfluid part was the same as a Bose–Einstein condensate in a helium gas. Landau thought that an ideal gas was hardly a realistic model for liquid helium, which is a highly dense system with strong interatomic forces. He considered it physically incorrect to treat helium atoms as if they were free particles in a gas, and set out to develop the then non-existent theory of quantum liquids.

In 1941 Landau published his own version of the theory of superfluidity based on a different main assumption. He postulated that at temperatures near to absolute zero – or not far from the ground state of lowest energy – liquid helium could be described with the help of quantized "elementary excitations". Elementary excitations behave in many ways like quantum particles, except that they cannot be identified with atoms or groups of atoms. They are instead the units of collective motion of the entire system, or of all atoms together. One example of such excitations was already well known in the form of the phonon, the quantum of sound waves or elastic vibrations in a crystal, which had been introduced by Igor Tamm in 1930. To explain superfluidity, Landau now postulated the existence of an additional type of excitation – the roton, or the quantum of vortex movements.

A number of the predictions from Landau's and Tisza's rival theories of superfluidity agreed with one another. Others, however, did not. These discrepancies allowed experimentalists after the war to opt for Landau's version. The most important difference between the two theories, however, was in the basic physical picture. Landau's solution was not limited to the phenomenon of superfluidity, but provided a general way of treating dense many-body systems that are governed by strong forces. The basic assumption that the lower excited states of any such system can be described by the elementary excitations has since been applied by Landau and many other physicists to numerous problems connected with solids, plasmas and liquids. The results were so impressive that the hypothesis of elementary excitations became, in the words of the theorist Philip Anderson, "probably the single most fruitful concept in all of solid-state physics".

Collective excitations became so familiar that today's physicists may wonder why Landau's hypothesis originally seemed so counterintuitive to people like Fritz London, who was developing a different approach in low-temperature physics. Since then, many new kinds of excitations have been discovered in condensed matter. They are often seen as synonymous with "quasiparticles", which is a related but somewhat more general notion. Other quasiparticles that were introduced into physics at about the same time are the hole (Yakov Frenkel, 1926), the exciton (Frenkel, 1931), the polaron (Solomon Pekar, 1945) and the plasmon (David Bohm and David Pines, 1951). Landau specifically relied on Tamm's phonon (1930) when he developed his theory of superfluidity.

Although the originators of the various quasiparticles pursued somewhat different approaches, they all shared the same attitude to the basic problem of freedom. Perhaps the central challenge for condensed-matter physicists at the time was to conceptualize the state of freedom of particles in densely packed bodies. Electrons in metals, for example, were treated as free particles in band theories of conductivity. In theories of ferromagnetism, however, the same electrons were usually assumed to be bound to particular atoms. Similar dilemmas arose in practically every major area in the field.

Landau – as well as Frenkel, Bohm and a few others – saw both free and bound approximations as far too crude. They searched instead for more complex mathematical models of freedom along "collectivist" lines, whereby particles would be sufficiently free but not entirely independent of each other. The various solutions they found now usually come under the general heading of "quasiparticles" and have since become the central concept of the collectivist approach in many-body physics. It is not entirely coincidental that most of the physicists who introduced such notions and methods into physics viewed collectivism in a positive light and sympathized with various versions of socialist ideas.

Physics and socialism

Landau's socialism was highly unorthodox. Although he was never formally affiliated with any political movement, his views gravitated toward the radical left, more so than was usually acceptable for the official Soviet line. He ridiculed "dialectical materialism" – the official Soviet philosophy of nature – especially when it was applied to science. However, he viewed "historical materialism" – the social theory of Marxism – as an ultimate example of scientific truth. If there had been a Soviet politician with whom Landau sympathized, it would probably have been Trotsky. Even before his arrest in 1938, Landau hated Stalin and shared the Trotskyites' left-wing criticism of Stalinism.

The year in prison, however, dramatically changed Landau's general assessment of the Soviet regime. He no longer regarded the Soviet society as socialist, but as a fascist dictatorship. Despite all the privileges, respect and recognition that he gained in the second half of his life – he received a Stalin prize in 1941 and was elected to the Soviet Academy of Sciences in 1946 – Landau continued to call himself a "scientific slave". In fact, he remained aware that the charges against him were never officially withdrawn – and that somewhere in the KGB files he was still classified as a political criminal.

Landau's basic scientific convictions also shifted at about the time he was in jail. Although he originally viewed the free-electron model of metals as unsatisfactory, he still could not avoid using it in the 1930s "at least to elucidate the limits of applicability of the existing theory". Later in his life, however, he rejected such models outright, whether it was the model of an ideal Bose–Einstein gas in helium or of the electron gas in solids. He relied instead on the method of collective excitations. His 1941 theory of superfluidity involved excitations that obeyed Bose–Einstein statistics.

In 1956 he developed another version of the theory of quantum liquids, in which elementary excitations satisfy Fermi–Dirac statistics. The approach based on electron-like quasiparticles has since replaced the model of electron gas as the main paradigm in the electron theory of metals. In 1959 the Fermi-liquid theory also allowed Landau's student Lev Pitaevskii to predict superfluidity in helium-3, which was subsequently discovered in the Nobel-prize-winning experiments carried out by David Lee, Douglas Osheroff and Robert Richardson in the early 1970s.

It was Landau probably more than anyone else who elevated quasiparticles to fundamental objects in contemporary physics. But his scientific influence was not just due to his theories or his *Course of Theoretical Physics*. He also commanded a strong following of younger physicists, known as the Landau school, who consistently and diligently applied the spirit of his approaches to many important problems in the field. Their impressive successes helped to create the standard language of many-body and condensed-matter physics. Thus, ironically, even physicists who had never cared about socialism or collectivism – or those who worked for big US corporations – began speaking and thinking in the language of collectivism when doing physics.


AIP EMILIO SEGRÈ VISUAL ARCHIVES

On a pedestal – a strong cult of personality grew up around Landau in his later years, thanks mainly to his closely knit research group. Landau is shown here in 1961 at Palanga, a Baltic Sea resort in Lithuania, shortly before his near-fatal accident.

The structure of Soviet science was very well suited to the existence of "scientific schools" such as that of Landau. His group functioned as a collective in the Soviet sense of the word, with a characteristic mixture of camaraderie, cohesion and hierarchy. It also allowed a strong "personality cult" to develop about Landau.

Tragedy struck in 1962 when Landau was at the height of his influence and fame. He barely survived a car accident and was never able to work again. However, his immense scientific contributions were recognized later that year with the award of a Nobel prize for his pioneering theories of condensed matter, particularly liquid helium. Both the accident and the prize boosted his aura still further.

Landau died in 1968 at the age of 60, but the school continued its productive work even after his death, with its main base moving to the Institute of Theoretical Physics near Moscow. It can be said that the Landau school still exists – even after the dismantling of Soviet science – although now probably more in the spiritual than the institutional sense.

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