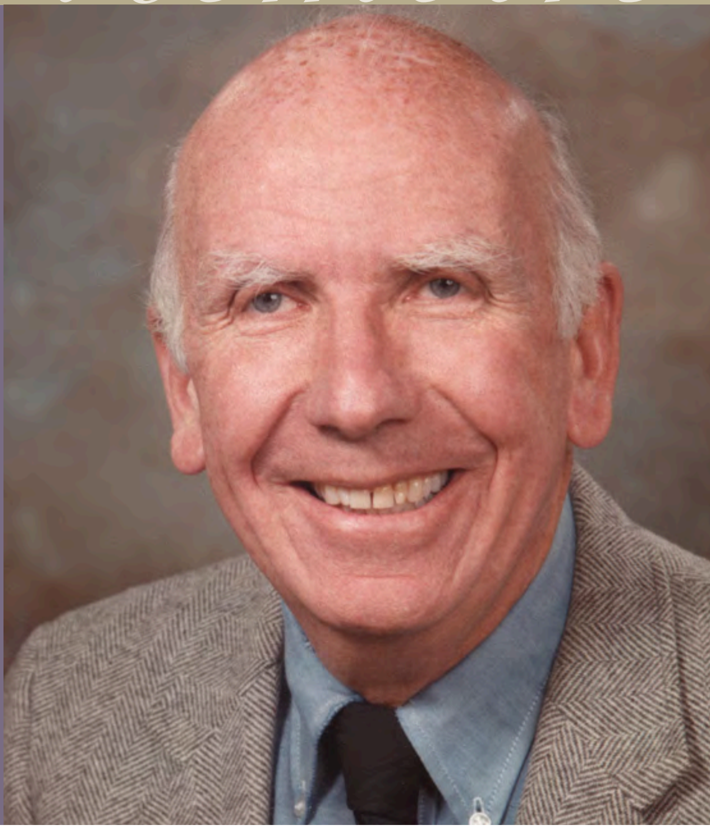
Leon Knopoff

1925–2011

BIOGRAPHICAL *Memoirs*



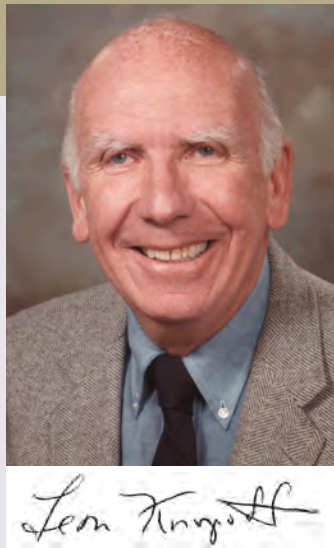
A Biographical Memoir by
Paul Davis
and Freeman Gilbert

NATIONAL ACADEMY OF SCIENCES

LEON **KNOPOFF**

July 1, 1925—January 20, 2011

Elected to the NAS, 1963



By Paul Davis
and Freeman Gilbert

Leon Knopoff, one of the foremost seismologists of the twentieth century and a man whose many talents spanned the arts and sciences, died at his home in Los Angeles on January 20, 2011. He had the rare distinction of being simultaneously a professor of physics, a professor of geophysics, and a research musicologist at the University of California, Los Angeles (UCLA). One of the youngest members to be elected to the National Academy of Sciences, at age 37, he continued to earn recognition from his scientific peers throughout his career. Knopoff was a generous man, dedicated to his family and to teaching his students.

Leon Knopoff was born in Los Angeles, California, on July 1, 1925. He was the son of Max and Ray Knopoff, immigrants from Russia, who arrived separately in America in 1914 and 1912, narrowly avoiding the turmoil in Russia caused by World War I and the Russian Revolution. The political upheavals coupled with the Stalinist regime effectively disconnected the Soviet and American branches of the family, a connection that Knopoff was able to re-establish many years later, thanks to his career in geophysics.

The Knopoff family lived in Boyle Heights, Los Angeles, within a large, closely knit, working-class Jewish neighborhood. An only child, he was sheltered by his parents from financial concerns, but moves to multiple abodes revealed the fact that the family faced financial struggles. He attended public schools and after an IQ test that revealed an extraordinary mind, he was accelerated two grades. He graduated from Roosevelt High School in 1941.

Before he was born, his mother worked as a seamstress in the garment district in Los Angeles, but gave up work to tend to the family, returning to work after his father died in 1946. The family enjoyed listening to classical music on the radio and attending movies and concerts. His mother attended the Hollywood Bowl in the year it opened.

His father had a fine voice and sang in a choral society. Both parents played mandolin in a mandolin orchestra. His father was trained as a carpenter, but in the lead-up to the Great Depression, carpentry was in low demand, so to protect the family's interests he became a milkman, recognizing that milk would always be needed. During the Great Depression, a customer who was unable to pay his bill bartered a somewhat worse-for-wear piano in exchange. The piano had a good tone and his father, with his carpentry skill, refurbished it with a mahogany finish. Young Knopoff was quick to take advantage of this addition to the family fortune, and he eventually took piano lessons at the Los Angeles Conservatory of Music and Arts. He showed a remarkable talent as a musician and won the Bach prize year after year, a prize he modestly recalled as one awarded to the person who could remember more Bach than anybody else, no matter how badly played [Knopoff oral history (KOH) recorded for the UCLA library 2003]. His memory was remarkable and may have been close to photographic, which served him well in future academic pursuits.

During his first semester at LACC, he did so well in physics that his instructor, a California Institute of Technology (Caltech) physics graduate, Ralph Winger, suggested he take the Caltech entrance exam, of which Knopoff was previously unaware. He passed the exam, but did not have the funds for the tuition, and so Knopoff returned to LACC.

After graduating from high school with distinction, it was clear Knopoff was destined to go to university, but to do what? In the circles in which his family socialized, college careers in subjects such as science or engineering were unknown. He had heard about engineering while at high school, and his parents had an acquaintance who was a civil engineer. So, in 1941 he enrolled in civil engineering courses at LA City College (LACC). LACC provided inexpensive preparation for an engineering degree that could be completed with a final two yearsat the University of California, Berkeley. The LACC campus was also a convenient streetcar ride from home, whereas other possibilities such as UCLA were more distant, both geographically and financially.

Knopoff was the first of his family to attend college. During his first semester at LACC, he did so well in physics that his instructor, a California Institute of Technology (Caltech) physics graduate, Ralph Winger, suggested he take the Caltech entrance exam, of which Knopoff was previously unaware. He passed the exam, but did not have the funds for the tuition, and so Knopoff returned to LACC.

The next summer, he re-took the entrance exam and then worked as a surveyor's assistant in San Diego. With money in his pocket from his summer's work, he transferred to Caltech engineering after one and a half years at LACC. He enrolled in the electrical engineering program at Caltech in 1942, graduating cum laude in 1944 at age nineteen.

A close friend at the time, who also transferred to Caltech from LACC, had enrolled in physics. Comparing notes with his friend on the subjects they were studying, it soon became clear that physics was much more intellectually interesting to him than electrical engineering. So, he took as many mathematics and physics courses as he could in his final year of engineering and transferred to mathematics and physics as a graduate student.

Knopoff was exposed to the exciting developments in physics occurring at Caltech at that time. He attended physics lectures from Nobel laureates such as Robert Millikan and Richard Tolman. He no doubt heard about earthquake studies and the Caltech Seismological Laboratory run by Beno Gutenberg (whose National Academy of Sciences obituary he wrote almost sixty years later). And, though he was only age seven at the time, Knopoff experienced the 1933 Long Beach earthquake. There are records of him commenting on such.

As a graduate, he tried his hand at mathematics but soon found that physics was more to his taste. His thesis, which was supervised by William H. Pickering (eventual director of the NASA Jet Propulsion Laboratory), involved measuring the interference of frequency modulated (FM) waves in the canyons and mountains around Los Angeles. FM radio had recently been developed, but the high frequencies generated shadow and interference zones. Every day Knopoff arranged for the technicians at the newly built FM radio station KHJ-FM to send out a test signal at noon that he would specify. He detected the signal with an antenna mounted on a van in the canyons of the Santa Monica Mountains to study the interference effects from the scattered radio signals.

Electromagnetism was to become a central theme in his early scientific career, as he translated the well-established formalisms of electromagnetic theory to the study of earthquakes and seismic waves. Part of his graduate education involved taking a course in electromagnetism from William Smythe, author of the well-known textbook *Static and Dynamic Electricity*, and he thoroughly enjoyed tackling the rather challenging problems in the book. He impressed Smythe with an elegant solution to one of the more difficult problems, for which Smythe himself had obtained a series solution. As a homework problem, Knopoff summed the series and represented the solution in compact form.

Knopoff recalled (KOH) how during his oral exam, Smythe was a calming influence, providing Knopoff with a few words to "relax" him at a point when calm was indeed needed.

During his PhD research, his advisor, Pickering, became more and more involved with the Jet Propulsion Laboratory, and so Knopoff was left very much on his own. While he later felt the thesis work was respectable, he said that his lack of experience compromised the writing, and the less said about the thesis the better. He was also sensitive that, being a study in electromagnetism, it was more nineteenth-century (classical) than twentieth-century (modern) physics, and so it did not have the kudos of the subjects his peers were studying. But he enjoyed the symmetries in classical physics, especially electromagnetism, influenced by Smythe, for whom he had great regard.

His father died in 1946 and, as the family finances became limited, rather than finish his PhD at Caltech and bring a financial burden on his mother, who had returned to work in the garment district, in 1948 he took a job in the Midwest as assistant professor in the physics department of Miami University in Oxford, Ohio, carrying his thesis material with him. At Miami he completed assembly of his thesis. The following year he submitted the thesis, traveled back to Caltech for its defense, and received his PhD in physics and mathematics (cum laude) from Caltech in 1949.

After his thesis defense, with a free summer before him, he was looking forward to relaxing for a while when the phone rang. Louis Slichter of UCLA asked if he would be interested in working in the university's geophysics lab over the summer. Slichter had been talking to colleagues at Caltech who had high recommendations for Knopoff.

Louis Slichter, the first permanent director of the Institute of Geophysics at UCLA, was to have a long and profound influence on Knopoff 's career. Immediately after World War II, it was recognized that because of research that enabled ultrasonic and electromagnetic detection of enemy vehicles, the new field of geophysics had contributed significantly to the war effort. Its importance for exploration for natural resources was also being recognized, but because the discipline fell between established fields of physics and geology, it was not well represented in university departments. In 1944 and 1945, the faculty at UCLA proposed establishment of the Institute of Geophysics at the University of California. The institute was formally established in July 1946 with the charter to conduct research "in the physics of the atmosphere, of the ocean, and of the solid earth." Louis Slichter, who had been involved in war-related geophysics in both World War I and World War II, was appointed its director in 1947.

Slichter began a campaign to recruit an exceptional group of scientists to the new institute. These included David Griggs, George Kennedy, Gordon MacDonald, and Willard Libby, the Nobel laureate. Knopoff responded positively to the phone call and Slichter suggested he come to work the following week. However, Slichter would not be there when Knopoff arrived; Slichter was traveling the next day for a six-week tour of Canada, leaving Knopoff to his own devices.

Knopoff began work the following Monday, assessed the situation, and began a series of model seismic experiments using piezoelectric transducers mounted on a block of wax. Having never met his employer, and once again being left on his own, he wondered what would be the reaction of the great man—director of the institute, member of the National Academy of Sciences, a man with a string of important papers to his name—to a fledgling geophysicist working with a block of wax, albeit well-categorized.

It did not help that a faculty member pulled his leg regarding how ferocious Slichter could be. Knopoff recalled how all trepidation vanished upon meeting the kindly, unassuming man who had nothing but encouraging words. Slichter was sufficiently impressed to offer him a position as research assistant in geophysics, beginning immediately. Knopoff, though tempted, declined, as he felt obliged to return to Miami University and continue teaching, rather than leave them in the lurch at the last minute. He returned to Miami where he was immediately promoted to associate professor. However Slichter was not the kind of man to give up.

Back at Miami, Knopoff broadened his academic interests to music and physics. He formed a two-piano team with a music department professor. They played for music classes and on the local radio station. Also, he taught a course in musical acoustics for the music department. He became intrigued with Slichter's papers and began a correspondence with him, the content of which reminds one of the words of George Bernard Shaw: "A man never tells you anything until you contradict him."

In a letter to Slichter (March 20, 1950), Knopoff wrote, "I hope you will forgive my presumption in continuing my comments on your paper…," a paper that had been published seventeen years earlier in the journal *Physics* (volume 4, issue 12). He disputed Slichter's contention that because measurement could not be made beneath the surface of the Earth to obtain vertical derivatives, the key equation to infer electrical properties inside the earth was inapplicable. Knopoff pointed out that if the current sources were elevated, the required derivatives could be measured. In addition, he noted various typographical errors in the paper. Slichter's response was (a) to "tell" him UCLA had approved his appointment to the research staff and (b) to publish a joint paper on the topic not long after. Thus began a long-term relationship with Slichter of friendship and collegiality as Knopoff rose in the academic ranks. Knopoff was appointed assistant research geophysicist in the Institute of Geophysics at UCLA on July 1, 1950.

For a person who brought much prestige to UCLA, was elected to all the academies, and won the most prestigious prizes (see Appendix), he got off to a rather slow start. His first paper appeared in 1952, two years after his appointment, and as even he admitted (KOH), it was a fairly meager one at that. He was learning his new field of geophysics, with the complete support of Slichter, who provided no hint of criticism.

Initially Knopoff's salary was paid with a grant from the General Petroleum Corporation. Various unsuccessful attempts were made to have Knopoff's employment status changed to the professorial series, which would have brought a concomitant responsibility of the university to find his salary. In a 1955 letter to Dean Knudsen, Slichter requested that Knopoff be appointed to the faculty or to associate research geophysicist in the research series, noting he had now published four papers and "he combines ability in electronics and in experimental work, with outstanding competence in theoretical and mathematical geophysics." Knopoff was jointly teaching with Slichter "Geophysical Prospecting" and Slichter noted he was the leader of their joint research with industry, the Geophysics/Seismic Scattering Project, and that he was being solicited to join industry research laboratories. The promotion in the research series to associate research geophysicist was approved, but promotion to the academic series was not.

In 1956 a faculty position became available in the institute and all the post-docs hoped to get it. Knopoff was very hopeful. After a visit to the east coast, where he had met a brilliant young professor at the Massachusetts Institute of Technology (MIT), Gordon MacDonald, Knopoff described him in glowing terms to Slichter. One might imagine his chagrin when the professorship went to MacDonald.

The disappointment, if indeed there was any, did not last long; Knopoff was appointed associate professor with tenure one year later. He also wrote several influential papers with MacDonald shortly thereafter. Knopoff's eventual appointment followed Slichter's letters to the university administration, which took on a note of urgency: "I have obtained information that MIT is planning to offer him a tenure position soon." Slichter was joined by two deans, Dean Young and Dean Dodd, who urged for Knopoff to receive an associate professor appointment. At last the university allocated an associate professorship with tenure, beginning July 1957. Knopoff was fast emerging as a prime target for recruiting.

On February 1, 1960, the chairman of the Department of Geology, University of California, Berkeley, wrote to Slichter that "This Department needs a theoretical seismologist, and we intend to request such an appointment. Professor Knopoff would be our choice by far over other possible candidates." He went on to say that perhaps a joint appointment would be acceptable, with a commitment that Professor Knopoff attend the Berkeley campus at least one semester each year. The subsequent correspondence reveals that it was left up to Professor Knopoff whether to take advantage of this offer, bearing in mind it would involve something of a "dual life." It appears the offer was declined.

After his slow start, the publications started coming at a prodigious rate. Knopoff wanted to have more contact with students than was available in a research institute. So, he approached the Physics Department and gave courses there. As a result, on his promotion to full professor, he found to his surprise that he was promoted to professor of both geophysics and physics in 1961.

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In 1962 and 1963, Knopoff was recruited by Frank Press, the new director of the Seismological Laboratory at Caltech. (Press eventually served as science advisor to President Carter and he was elected president of the National Academy of Sciences). As this new position would be in the top seismological laboratory in the country, perhaps the world, and Knopoff would be working with luminaries such as Hugo Benioff, Charles Richter, Beno Gutenberg, and Frank Press, the invitation to join them was hard to resist. Knopoff took leave of absence from UCLA for one year and accepted the position. He found that, while the science was superb at Caltech, he had developed deep interests outside his field in music theory and philosophy, which were more easily accommodated at a university such as UCLA than at an institute of technology. Knopoff said (KOH) that the invitation to join the Institute of Ethnomusicology was an "instrumental ingredient in my returning to UCLA from Caltech." Also the Seismological Laboratory was remote from the main campus, which made interaction with students difficult. And so Knopoff returned to UCLA, but not without forging strong linkages with the faculty at Caltech, especially Frank Press.

With a PhD in electromagnetic theory, Knopoff was well qualified to comment on Slichter's 1933 paper on electromagnetic deep sounding of the Earth. That paper developed the theory for inverting electromagnetic signals returned from the Earth to infer the underground distribution of electromagnetic properties such as conductivity and dielectric constant. One may surmise that this early interaction established two characteristics of his scientific approach that were to be hallmarks of his career. The first was an appreciation of the power of theory, and the second was scientific inference based on cautious statistical inversion of data.

As a research associate, Knopoff would have known that one of the first people to read his papers would be Louis Slichter, who would expect a certain theoretical standard, comparable to the great elasticians and seismologists of the time, including Jeffreys, Lamb, Love, and electromagneticists such as Kirchhoff, Poisson, Liouville, and Sommerfeld. He was then faced with the challenge of developing theory that could stand alongside canonical solutions in geophysics, such as the famous Lamb's problem, an analytical solution for the seismic waves from a point force. This was a challenge, as we show below, that he met with remarkable success.

Slichter's unwavering support shows that Knopoff succeeded in impressing his nearest evaluator. One wonders what part this relationship of mutual respect played in keeping him at UCLA, in spite of offers at industry laboratories, MIT, the University of California, Berkeley, and Caltech. He remained at UCLA for the rest of his career. Willard Libby was appointed director after Slichter. Knopoff followed Willard Libby as director of the institute from 1972 to 1986, a fourteen year term, advisedly equal to that of his mentor.

We have remarked that his transition to geophysics was slow but deliberate. He said, "So I started to develop a set of ideas about developing seismology, seismic wave theory, in directions parallel to what had been developed for electromagnetic theory, which was a beautifully and highly developed subject dating back to the beginning of the twentieth century." (KOH)

During his career he published more than three hundred papers. The first publication in 1952, "On Rayleigh wave velocities," was a terse, one-page solution of the Rayleigh equation for arbitrary ratio of P wave to S wave velocity, extending the analytic solution that appeared in A. E. Love's classic 1944 book, *The Mathematical Theory of Elasticity*. This was followed by a series of three publications in 1954, and once the limiting static friction to publication was overcome, the papers appeared at an average of five to six per year on an extraordinary range of topics.

The scientific philosophy of his research approach in those days is well characterized in his own words:

> *Boundary wave problems in elastic wave propagation are somewhat more difficult to solve than the corresponding problems in electromagnetic theory. This is because of the fact that shear and compressional motions interact on boundaries and that we are interested in the solution of mixed boundary value problems of a particularly awkward type. In an attack on such problems, I have been able to develop approximation methods appropriate to these problems where exact solutions have not been forthcoming. Some exact solutions, but only for particularly elementary geometries, have also been obtained. The solutions to these problems have come from the realization that we can adapt the techniques at present in use in other disciplines involving wave propagation, such as acoustics or optics, to these problems in elastodynamic theory. Accordingly, I have attempted to construct a "physical seismology," in analogy with physical optics, wherein I have tried to solve some problems in the scattering, absorption, diffraction, interference, etc. of seismic waves. (K files)*

Thus in 1956 his work took a theoretical turn, resulting in a famous paper for calculating ground motions arising from body forces and motions on a surface such as an earthquake fault. In that paper, Knopoff extended to the elastodynamic problem Kirchhoff 's retarded potential solution to the wave equation, thereby providing the elastic analog to Green's theorem. This was his first major paper. He called it "my first important paper" and one "that was my idea."

He noted that problems in electromagnetism are either solved by the harmonic method, where simple solutions are superposed to satisfy conditions on simple boundaries and are typically applied to far-field radiation problems, or by integral equations, such as those due to Kirchhoff, which suffered no such restrictions and could be used to model near-field phenomena such as diffraction. The integral method had received little attentionin the case of elastic wave theory, and he proceeded to develop the first integral solutions of elastodynamics. However, the formulation was significantly more complicated because both P and S waves are described. This paper and those that followed essentially established him as the leading theorist in elastodynamics of that time. The heritage of papers deriving the double couple model of an earthquake; the dependence of farfield displacement on slip velocity on a fault; and one of the milestones in the evolution of theoretical seismology, the representation theorem, published with Robert Burridge in 1964, can all be traced to that seminal paper.

After the 1956 paper, Knopoff garnered many canonical analytical expressions to his name by applying both classical and modern physics to the Earth. Of note is his elegant solution (1958) to the antiplane crack, which ranks in fame alongside the in-plane Starr crack (1928) and the Eshelby circular crack (1949). He solved Lamb's problem in a material with solid friction, developed inversion of surface waves, and constructed synthetic seismograms from superposition of normal modes. He developed an efficient method for solving problems of elastic waves in multilayered media, which was extended later in collaboration with Fred Schwab, and he developed the first computational solution to the fault-plane problem.

As head of the Seismic Scattering Project of the University of California, he and his colleagues published many of the canonical scattering papers, adopting electromagnetic approaches that were developed during the war for radar and radio communication, beginning with analytical expressions for scattering of seismic P and S waves by a sphere. With John Hudson he published on scattering of long waves by distributions of small objects. Then with Freeman Gilbert he looked at the complementary case of short wavelengths and large objects, and with Ajit Mal he studied scattering of surface waves by numerous geometric shapes.

H. Douglas Garbin and Knopoff published the first calculation of the average elastic properties of an elastic solid permeated by cracks. A. K. Chatterjee, A. K. Mal, and Knopoff published the first exact calculation of the elastic properties of a composite to second order in the concentration. The latter results are of importance in the field of non-destructive testing of materials permeated by hidden flaws. These papers showed that self-consistent methods of calculation were incorrect in the second order in concentration of extended inhomogeneities. Extension to the percolation limit at high densities was made with Paul Davis (K_files).

Kennedy and Knopoff are credited with discovering the application of thermo-luminescence for dating archaeological artifacts. Knopoff attributes the idea to George Kennedy, a geochemist who collected pre-Columbian artifacts as a hobby and wanted a tool to verify authenticity.

He worked on attenuation, and with Gordon MacDonald he argued that the reason solids activated by seismic waves exhibit frequency-independent Q, in contrast with liquids, must be due to non-linear effects. This theory was controversial because the amplitudes of seismic waves were so small that the strains were thought to be in the linear range.

He published several papers on finite-strain equations of state applicable to the deep Earth that were designed to extrapolate smoothly from laboratory conditions to the Thomas-Fermi equation at high pressures. The collaboration with MacDonald included investigation of the density of the core. Keith Bullen had used seismic methods to determine the core's density, and the iron-nickel (Fe-Ni) amalgam of iron meteorites appeared to be the best candidate. However, the Fe-Ni density, corrected for the enormous pressures and temperatures of the core, appeared too high. Knopoff and MacDonald were the first to use shock wave data and a high-pressure equation of state to show that indeed an extra light element was needed, and the preferred element was silicon (Si), which is still considered a candidate to this day.

Another controversy emerging at that time was the power source for the geodynamo that causes the Earth's magnetic field. There was debate as to whether, at the time of core formation, potassium could have combined with iron, which would provide a source of heat as its radioactive isotope decayed to argon. With his student Mark Bukowinski, Knopoff used quantum mechanics to investigate the properties of iron and potassium in the core, confirming that the inner core was predominantly Fe-Ni, while the outer core required a lighter element as well as Fe-Ni. They also proposed that an outer-shell electronic transition in potassium might justify its use as another alloying agent in the core, supporting the arguments for a radioactive source of energy, a subject on which there is still much debate.

Kennedy and Knopoff are credited with discovering the application of thermoluminescence for dating archaeological artifacts. Knopoff (KOH) attributes the idea to George Kennedy, a geochemist who collected pre-Columbian artifacts as a hobby and wanted a tool to verify authenticity. However, the implementation was Knopoff's. Kennedy came into Knopoff's lab inquiring if he could build an instrument to date pottery. Electronic

states of a crystalline material subjected to natural radiation are excited during the time the pottery is produced. On reheating, the excited states are reset and light is emitted. The intensity of the emitted light is directly proportional to the age of the object. Knopoff built the instrument. It was calibrated by subjecting samples to known doses of radiation from the UCLA cyclotron. He obtained excellent agreement between the thermoluminescence date for pottery from Athens and the stylistic date.
The approach is still utilized today in archeology and art history.

In the early 1960s, the United States and Soviet Union signed treaties not to conduct atmospheric, outer space, or oceanic nuclear tests. But no treaty was signed for underground tests. So, there was a need to monitor what unfriendly countries were doing. The program to identify and detect underground nuclear events was established and funded by the Air Force, and it provided money for the development of geophysics in many universities. Knopoff was well placed to get involved, given his background in seismology. With the help of Frank Press, in 1960 he installed four high quality long-period seismic stations around the European Alps for one year, and then the next year the stations were moved to the western Mediterranean. These instruments, designed by Frank Press and Maurice Ewing, could measure surface waves of periods of up to a hundred seconds with great sensitivity. Shortly after these experiments, in 1964, the Air Force began to install the World Wide Standard Seismic Network, WWSSN, which included both short-period and long-period seismographs of this design installed at stations in friendly countries across the globe. The Air Force made the data available to university researchers. Funding for university seismological research was ensured when Press and colleagues, based on their analysis of global seismic data, presented to the military precise times and locations of supposedly secret United States nuclear tests in the Pacific.

The fieldwork in Europe was coupled with a rather remarkable sabbatical leave in 1960 and 1961 at the University of Cambridge, in England. There he developed analysis procedures to invert the seismic recordings for Earth's structure. The analysis revealed for the first time a low velocity channel under the Alps. Most seismic investigations found that velocity increases with depth in the Earth, attributed mainly to the increasing pressure. That the trend reverses suggested that between the competing effects of pressure and temperature, the latter had begun to dominate. As early as 1932, Gutenberg had used the variation of amplitudes from P body waves to deduce the presence of a low velocity zone in the upper mantle, but the response to his approach was great skepticism. Knopoff provided the first surface wave confirmation.

In addition, in 1960, while on sabbatical in Cambridge, Knopoff gave a lecture on thermoluminescence at Oxford University. This lecture was the basis for the formation of a famous thermoluminescence lab at Oxford. He was then invited to join an archaeological expedition to the Dead Sea. He combined this with a gravity survey across the Jordan River, just north of the Dead Sea (Knopoff and Belshé 1966). Among the stations visited, which included Jacob's Well, Jerusalem (Qalandaiya) Airport, Bethlehem, and Jericho, he obtained permission to make a gravity reading at Amman (Marka) Airport in Jordan. But, in case the gravimeter was a bomb and not a scientific instrument, he was supervised by a guard who pointed a gun at his head while he took the reading. The published profiles show that the Amman reading was consistent with the others, and that even though his mind may not have been calm, his fingers apparently were, in spite of this adversity.

He caught infectious hepatitis in Jordan that became severe on return to Cambridge. His fiancée, Joanne Van Cleef, had to be telephoned in the United States to say that the groom was in a hospital in Cambridge, England, and that he could not make the wedding.

He caught infectious hepatitis in Jordan that became severe on return to Cambridge. His fiancée, Joanne Van Cleef, had to be telephoned in the United States to say that the groom was in a hospital in Cambridge, England, and that he could not make the wedding. The wedding took place two months later, and both of them returned to Cambridge to complete the sabbatical. So began a fifty-year relationship of mutual support that helped him throughout the remainder of his life, both in triumph and adversity.

With a well-funded lab and a burgeoning reputation in the mid-sixties, Knopoff began to attract students and post-docs with an impressive array of quantitative skills. The WWSSN provided a rich source of data. Knopoff's group began to develop the theories and analysis techniques for these data in earnest, adapting them to then newly developed mainframe computers.

Plate tectonics was in its infancy. The seminal Vine-Matthews paper on magnetic stripes associated with sea floor spreading was published in 1963, but details on plate thickness and motions relative to the mantle were unknown. Knopoff provided the vertical dimension of plate tectonics by initiating a search for low-velocity channels across the globe. For example, under the Pacific he discovered the low-velocity channel that extended from 100 to 200 km depth. It soon became recognized as defining the base of the Pacific plate and the zone-decoupling moving plate from the underlying mantle. Similar low-velocity zones were found beneath all the oceans and tectonically active regions on continents. In contrast, continental shields developed no such low-velocity zones. This explained why the continental plates move much slower (centimeters per year) through the mantle than the oceanic plates, rather as if they have a deep keel. The Pacific plate travels fastest (10 centimeters per year). Thus, the work of these early days showed that the Pacific plate was one of the major drivers of the global convective circulation of plate tectonics.

Knopoff in China, 1980.
(Photo courtesy Joanne Knopoff.)

Much of the globe was covered by WWSSN long-period stations in the mid-1960s, but the geopolitically neutral Antarctic continent still had none. Knopoff was awarded a grant from the National Science Foundation to establish a seismograph at a Russian station, Novolazarevskaya, on the coast of Antarctica, and a matched station at the South Pole itself. By analyzing seismic waves along the path between the two stations, he showed that indeed Antarctica had a continental structure with a deep keel.

Slichter had been running tidal gravimeters both at UCLA and the South Pole that also served as long-period seismometers. With Slichter's passing in 1978, Knopoff took over the South Pole project.

The South Pole was a special location for tidal and earthquake studies. The response of the solid Earth to diurnal and semi-diurnal tides was known to be elastic, whereas the response to loadings such as the removal of the ice sheets over 10,000 years or so was more fluidic. So, there was interest is measuring the response at longer periods such as the 14-day, monthly, and 18.6-year lunar tides. South Pole was ideal to search for these periods because the diurnal and semi-diurnal tides were absent there. However, for Knopoff it had other desirable features.

It was well known at the time that when a large earthquake occurs, the Earth vibrates with a series of normal-mode frequencies that depend on its internal structure. Slichter, along with groups at Caltech and Lamont Observatory, was the first to unambiguously measure the Earth's modes in 1960 when the largest ever-recorded earthquake (magnitude 9.5) struck in Chile. As this new field of "terrestrial spectroscopy" became a subject in its own right, it became recognized that the asymmetry caused by rotation and ellipticity of the Earth causes the frequencies of the modes to be split from values that they would have if the Earth were spherical and stationary, rather like the Zeeman effect. Modes measured by a long-period station at South Pole, because of its symmetric location, were free from such splitting, and so other effects, such as those from lateral heterogeneity or hitherto undiscovered modes, might be observable.

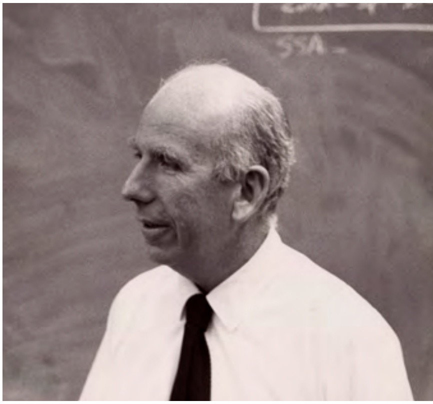
One such mode, the Slichter mode, involves displacement of the Earth's inner core by a large earthquake and subsequent oscillations. In 1961, Slichter predicted that it should have a frequency of several hours dependent on the density contrast between inner and outer core. (The analytic expression in his paper was left as an exercise for the student.) In spite of a thorough and systematic search, including removal of all residual tidal effects, the Slichter mode proved elusive, not helped by the fact that no event as large as the 1960 Chile earthquake has ever occurred since. (Observation of the Slichter mode was reported in data from superconducting gravimeters in Europe by Spiros Pagiatakis and colleagues in 2007, but multiple confirmations are still needed.)

Knopoff 's international collaborations were legendary. He worked with Edgar Kausel (Chile), Stephan Mueller (Germany), Giuliano Panza (Italy), Keilis-Borok (Russia), Chen Yuntai (China), and Teruo Yamashita (Japan). The list is too extensive to complete here, and at all of these institutions he was appointed visiting professor. Knopoff, who had been limited to streetcar rides near Boyle Heights in his youth, became an academic traveler of some virtuosity, thanks to exposures at international meetings such as the 1957 International Union of Geodesy and Geophysics meeting in Toronto. Knopoff 's interaction with Soviet scientists began at this meeting, where he met long-term collaborator Vladimir Keilis-Borok of the Soviet Academy of Sciences.

Beginning in the early 1960s, Knopoff traveled to Moscow to collaborate with Keilis-Borok. Thus began a long-term relationship of exchange visits that persisted through the Cold War, culminating with an invitation to Keilis-Borok to join Knopoff permanently at UCLA in the late 1990s. Keilis-Borok was instrumental in reuniting the Soviet and American branches of the Knopoff family when he located Knopoff 's uncle in Leningrad.

Keilis-Borok's group was applying pattern recognition and statistical methods developed by Russian mathematicians, such as Gelfand and Kolmogorov, to the problem of earthquake prediction and other geophysical phenomena. A joint USA/USSR Working Group on Earthquake Prediction was formed to pool expertise in the two countries.

The Russian school was also strong in inverse theory. In the inverse problem, one wishes to determine the properties of an inaccessible region from measurements at selected locations, usually on the surface. Knopoff had shown that the geophysical inverse is non-unique—that is, one can never determine the properties of the inaccessible region with precision—and hence, it is incumbent upon geophysicists to indicate the range of uncertainties in their interpretations. Keilis-Borok, Knopoff, and a number of students developed the hedgehog method of inversion, which directly specified the class of solutions consistent with the data. Like a hedgehog eating out the interior of a bush, the method explores the volume of solutions compatible with the data. The method is still occasionally used in the problems of geophysical inversion. Knopoff and Jackson constructed a solution to the problem of overparameterization of structure—that is, how to fit the detailed structure of the Earth with insufficient data.



Knopoff in his office, 1967.
(Photo courtesy Joanne Knopoff.)

At the 1960 IUGG meeting in Helsinki, incoming president of the union, Vladimir Beloussov, proposed the Upper Mantle Project, an international program for study of the structure of the Earth's crust and the shell beneath it. Beloussov was elected chairman of the project and Knopoff its general secretary. The United States' participation had to be approved at the Presidential level. Knopoff and colleagues testified before the President's Scientific Advisory Committee. The approval took the form of a telegram from then-President Lyndon Johnson, which Knopoff communicated to the IUGG, and which had the effect of both increasing United States funding for geophysics and advancing global collaboration.

One of the more active working groups of the Upper Mantle Project, focused on geophysical theory and computers, was led by Keilis-Borok. When the project wound down, Knopoff used the working group as a basis for founding the Committee on Mathematical Geophysics, which continues to hold biennial meetings even to this day.

Knopoff 's most famous paper is one he published with Robert Burridge, in 1967, on "Model and Theoretical Seismicity." They constructed one-dimensional models of earthquakes using masses, attached to springs, that slid on a frictional substrate, the so-called "slider model," to serve as a basis for earthquake simulations. These devices, operated physically or simulated with a computer, reproduced the earthquake statistics known at the time.

For example, it was known that the plot of the logarithm of the number of shocks above a given magnitude versus magnitude fell on a straight line of negative slope b=1, which is known as the Gutenberg-Richter relation. Also, the frequency of aftershocks decayed in time as 1/time, which is known as the Omori Law. Knopoff and Burridge showed that aftershocks relied on processes involving time delays, which they synthesized using viscous elements. They found that the unloaded system generated small shocks while being loaded to a critical energy, above which large shocks were generated. After reaching the critical point, the resulting shocks were clustered in time, with aftershocks generating aftershocks, rather than following a random Poisson process. The shocks obeyed the Gutenberg-Richter and Omori relations. They showed that radiated seismic energy was a small fraction (12 percent) of the change in potential energy of an event—that is, seismic efficiency is low. All these effects, seen in modern catalogs, were generated by the simplest model, which captured the essential physics. The paper was later regarded as one of the most important models in condensed-matter physics, a subject that was not developed until more than a decade later.

Following this paper, Knopoff continued his concerted effort to understand statistical seismology, which earned him the title, "the father of statistical seismology."

Earthquake prediction has had mixed success. Early results, usually based on precursors recognized in hindsight, seemed very promising, but with time it has become apparent that prediction in a narrow four-dimensional box of space and time (kilometers and days) remains elusive. However, statistically-based forecasting in broad regions (hundreds of kilometers and years) has had more success, at least in a statistical sense.

Knopoff and his collaborators established how rigorous statistical testing of prediction claims could put them in perspective. He collaborated on the project first with Robert Burridge, then with John Gardner, Yan Kagan, and later with Didier Sornette. One of his 1974 papers with Gardner on earthquake catalog declustering is still widely cited. In the mid-1970s he collaborated with Yan Kagan on statistical analysis of earthquake catalogs and stochastic models of earthquake occurrence. They worked on the development of a comprehensive theory of earthquakes, including sudden increases in precursory seismicity, aftershocks, and foreshocks. He and Kagan established the statis-

Knopoff and Kagan were the first to employ the results of statistical analysis to numerically forecast the probability of earthquake occurrence in time and space, and to evaluate quantitatively the forecast skill.

tical validity of the inverse 1/t Omori law for foreshocks. Among problems investigated were earthquake size distribution; dependence of earthquake inter-relationship on size, depth range, and temporal intervals; fractal features of earthquake spatial and temporal distribution; and quantitative studies of earthquake focal mechanisms.

Knopoff and Kagan were the first to employ the results of statistical analysis to numerically forecast the probability of earthquake occurrence in time and space, and to evaluate quantitatively the forecast skill. They developed the first clustering models of earthquakes based on first principles, including stochastic branching, clustering, irregularity, triggering, and scale invariance (Kagan and Knopoff, 1981) predating the highly successful Epidemic Type Aftershock Sequence model, published by Ogata in 1988, that is being used today in operational forecasting of aftershocks.

As his career developed, Knopoff became interested in applications of complexity theory to different disciplines.

> *How does one assemble small building blocks into large structures that have pattern…Earthquakes are an example as small earthquakes organize into a large one. Music is another. Notes are organized into a symphony, and different composers, Beethoven and Mozart for example, can be recognized from indefinable patterns that allow us to distinguish jazz from classical or oriental music. In the same way, letters or words are organized into language whose patterns distinguish French from English, Spanish from Russian. It is not quantitative. The brain does not analyze letters individually, or consonants and syllables. It makes an abstraction, and even if you do not know the meaning of the French or Russian, you can recognize it as French by the music. (KOH)*

As well as elucidating the phenomena of selforganization and chaotic behavior in seismic systems, he pioneered pattern recognition in musicology and literature. For example, he characterized authors or composers by repeatable patterns. He recognized the following: “In all phenomena long-range correlation plays a vital role in its self-organization, and hence nearest-neighbor structural analysis, such as through Markov process analysis, is not justified. In the area of musical structure, these problems are even more intricate because several sensory detectors (of tonal duration, pitch and loudness) are all in interactive play simultaneously." (KOH)

At the time Knopoff recorded these thoughts, the new field of condensed matter physics was being developed. Per Bak had coined the term "self-organized criticality" (SOC) to describe an unstable sand pile, and Benoit Mandelbrot coined the terms "fractal" and "fractal dimension" to describe rough structures that appear in nature, such as coastlines, clouds, and topography. It was recognized that because the laws of physics and chemistry have no intrinsic scale, these dynamics and structures exhibited scale invariance. For physicists who had been approximating nature with simple geometries such as cylinders, spheres, and blocks, these were new and exciting developments.

G. J. Wasserburg toasting Knopoff on his 65th birthday. (Photo by Joanne Knopoff.)

Knopoff knew Mandelbrot from their days as students at Caltech. The Burridge-Knopoff model of a decade earlier became the case-example of condensed matter physics applied to earthquakes. The b value of Gutenberg and Richter was interpreted as the fractal dimension, resulting from the non-linearity of friction effects and the scale invariance of the fracture process; while the attainment of critical energy for large events was interpreted as a self-organized critical state. In the early 1980s, Mandelbrot became aware of the work of Burridge and Knopoff, as well as the work of Kagan and Knopoff that was being extended by Jean Carlson and Jim Langer at the Institute of Theoretical Physics at the University of California, Santa Barbara. Exchange visits took place. As a result, in the second edition of his book, The Fractal Geometry of Nature, Mandelbrot included a section on earthquakes.

At first, Knopoff enjoyed these developments in modern physics and the recasting of his approach into the modern vernacular. The statistical analysis of earthquakes was interpreted to imply that fault zones were in a state of self-organized criticality. But this concept led to the conclusion, by some, that earthquakes were intrinsically unpredictable. If a seismic zone was always on the point of criticality, long- and short-range interactions were equally probable. There was no chance of seeing precursors associated with a subcritical-to-critical transition, nor of identifying localized changes in geophysical measurements.

Knopoff found this view too pessimistic and based on an idea that may, or may not, apply. In the latter part of his career he became disenchanted with the SOC description, feeling the model had been pushed too far and had removed the incentive to look for precursors.

First of all, he argued, catalogs are dominated by aftershocks, which are small and not affected by boundaries, and so the scale invariance and SOC may be more apparent than real. The Earth is not an infinite system for which self-organized criticality applies at all scales. The Earth is scale-limited, in which finite dimensions, such as the depth of the seismogenic zone or the damage zone about faults, break the scale. He contended that catalogs, with aftershocks removed, do not exhibit scaleinvariance. He had established that earthquakes were not random events, but occurred in clusters, and that, were we to understand the physics better, earthquake forecasting should be possible, if not prediction itself. The work was left unfinished, but the structures Knopoff set in place leave room to hope for future success in this critical area.

Involvement with music

By the time Knopoff returned to UCLA from Miami, he was already interested in music as the organization of sound into language according to patterns. This interest was formalized when he became part of the Institute of Ethnomusicology, created at UCLA in 1961, with Mantle Hood as its director and senior faculty who included Charles Seeger and William Hutchinson of the Music Department.

Knopoff and Hutchinson taught a course called "Seminar in the Acoustics of Music."

Knopoff said that he thought of acoustics in an unusual way; in the course, he and the students looked into the psychological perception of music and how a culture organizes the available sound into language. This was also the focus of papers he wrote with Hutchinson.

A Caltech friend of Knopoff's later became a part-time music critic for a Pasadena newspaper. On occasion, from the mid- to late 1950s, he would ask Knopoff, who was then at UCLA, to substitute for him at a concert. Knopoff's concert reviews displayed deep knowledge of music and performance. At UCLA, after meeting physics professor David

Saxon (a lifelong friend and later University of California president), he started going to the Saxon home for evening gatherings of a group that played baroque chamber music. Saxon played recorder while Knopoff played Saxon's harpsichord.

During the year that Knopoff spent at Caltech (1962–1963), he met a technician at the Seismological Laboratory whose hobby was making harpsichords and other baroque-style instruments, and Knopoff bought a harpsichord from him. After that, for many years Knopoff hosted chamber music evenings at his home for a group that varied in size from a half dozen to a dozen musicians, who played violin, cello, flute or recorder, and occasionally viola or oboe. They met once or twice a month, occasionally at the home of one of the violinists, where Knopoff played piano (there being no harpsichord), and they met the rest of the time at his house, where he played his harpsichord. In later years, when the larger group no longer met, Knopoff continued for years to play every couple of weeks with two of the violinists, usually on the piano, alternating between his home and the home of one of the violinists.

Leon and Joanne Knopoff at the President's Dinner during the 1998 Annual meeting of the National Academy of Sciences. (Photograph courtesy Joanne Knopoff.)

Knopoff also played four-hand piano music regularly for many years with William Hutchinson. Knopoff had an extensive collection of four-hand piano music, much of which had belonged to Beno Gutenberg—a Caltech seismologist and colleague—and was given to him by Gutenberg's widow, Hertha, after Gutenberg's death. While traveling, Knopoff took the opportunity, when he could, to play the piano, for example with a chamber music group of academics in Washington, DC, or four-hand piano with Bertha Swirles, Lady Jeffreys (Sir Harold Jeffreys' wife), in Cambridge, England.

Teaching and his personality

Knopoff was a gifted teacher, extremely generous with his time, with an infectious excitement in describing science. He won the UCLA Physics teaching award four times for teaching undergraduates. He graduated thirty-eight graduate students. Visitors traveled from all over the world to study in his laboratory, including thirty-nine post-doctoral scholars, as well as other senior scientists. Students and visitors alike benefited from his extraordinary ability to teach complexity in the simplest of terms, with animation but patience to impart understanding.

Knopoff at a celebration in 2000 honoring his 75th birthday and 50th year at UCLA. (Photo courtesy Joanne Knopoff.)

He often used his sense of humor to emphasize a point. His famous paper, which has the briefest of titles, "Q," describes in detail the attenuation of elastic waves in the laboratory and in the Earth, and then provides thorough theoretical analysis of several mechanisms that might explain such attenuation. Published in 1964, "Q" continues to be widely quoted. In contrast, he published with John Gardner a paper that has the remarkably long title, "Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian?" followed by the shortest abstract, "Yes."

In avant-garde musical composition, during 1974 he copyrighted his own version of Mahler's "Das Lied von der Erde" in two (Earth) movements, composed with a computer. The first movement was based on seismicity from the 1952 Kern County earthquake, while the second was an accelerated digital recording of the normal modes of the Earth.

Extremely dedicated to his academic institution, Knopoff and his wife, Joanne, created in 2001 an important endowment in UCLA's College of Letters and Science. The Leon and Joanne V. C. Knopoff Chair in Physics and Geophysics was the first chair in the basic sciences to be endowed by a faculty member during the Campaign UCLA fundraising effort. This endowed chair supports the research of a promising young scientist in solid-Earth geophysics, encouraging research that will help us better understand patterns in complex systems and solid-Earth geophysics.

A story from Knopoff 's remote travels in the seventies illustrates his generosity of spirit. He was hiking in the mountains of Tajikistan with a Russian colleague when he came

Knopoff presenting a talk at a Festschrift honoring Vladimir Keilis-Borok in October 2001. (Photo by Andrei Gabrielov.)

across a group of shepherds, and through an interpreter he engaged them in conversation. Having established he was an American, he asked if he could take their picture. They agreed and asked, when he returned to America, if he would send them a print. When it came time to write down an address, he found that the lead of his pencil was broken, and so he pulled out his pocketknife to sharpen it. They expressed amazement, having never seen a folding knife before. So, he gave it to them as a gift.

After much consultation, as was their custom, they insisted on giving him a return gift and asked, "How about a sheep?" Knopoff recounted that he was, at this point, ten miles up a trail from the automobile, a small plane ride from Dushanbe, a further plane ride from Moscow, and that a sheep would be more trouble than its worth. So, they compromised: the shepherds started a fire and they all had a meal of mutton soup and bread. This example typifies the warm and generous man Knopoff was, someone who gave more than he got, whether it be while instructing students, interacting with shepherds or visitors, or imparting his generosity to his family who, with him, endowed the university with their personal wealth. His friends and colleagues knew him as a man of integrity, brilliance, humor, generosity, kindness, and modesty. Ever ready with a broad smile and a hearty laugh, he possessed an enormous sense of fun and adventure.

Knopoff was an extraordinary human being and a gift to all who knew him. He is survived by his wife Joanne and his children Katie, Rachel, and Michael, as well as a grandson.

ACKNOWLEDGEMENTS

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HONORS AND AWARDS

ELECTIONS

Fellow of the American Geophysical Union (1962)

Member of the National Academy of Sciences (1963)

Fellow of the American Association for the Advancement of Science (1964)

Fellow of the American Academy of Arts and Sciences (1965)

Fellow of Selwyn College, Cambridge, United Kingdom (1986)

Member of the American Philosophical Society (1992)

AWARDS

Emil Wiechert Medal of the Deutsche Geophysikalische Gesellschaft (1978)

Gold Medal of the Royal Astronomical Society (1979)

H. F. Reid Medal of the Seismological Society of America (1989)

Honorary member and recipient of the Golden Badge Award of the European Geophysical Society (2001)

Docteur Honoris Causa from Université Louis Pasteur, Strasbourg, France (2004)

First honorary professor of the Institute of Geophysics of the China Earthquake Administration (2004)

SERVICE [PARTIAL LIST]

Director of the Institute of Geophysics and Planetary Physics at UCLA from 1972–86

Member and Secretary General of the International Upper Mantle Project

Founder and Chair of the International Union of Geodesy and Geophysics Committee on Mathematical Geophysics

Chair of the US Upper Mantle Committee

Chair of the US Committee for the International Association of Seismology and Physics of the Earth's Interior

Chair of the Ad Hoc Committee on Seismology and Aftershocks, US Atomic Energy Commission

Editor of *Non-Linear Processes in Geophysics*

Associate editor of *Reviews of Geophysics and Space Physics*

Associate editor of *Journal of Geophysical Research–Solid Earth*

Further information may be found at http://www.leon.knopoff.com

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