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Philip Warren Anderson

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Journal

Biographical Memoirs of Fellows of the Royal Society

ISSN

0080-4606

Authors

Chandra, Premala

Coleman, Piers

Yu, Clare C

Publication Date

2026-08-26

DOI

10.1098/rsbm.2025.0029

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PHILIP WARREN ANDERSON
13 December 1923 — 20 March 2020

Biogr. Mems Fell. R. Soc.



Phil W. Ashm

PHILIP WARREN ANDERSON

13 December 1923 — 20 March 2020

Elected FRS 1980

BY PREMALA CHANDRA¹, PIERS COLEMAN^{1,2} AND CLARE C. YU^{3,*}

¹*Center for Materials Theory, Department of Physics and Astronomy,
Rutgers University, 136 Frelinghuysen Rd, Piscataway, NJ 08854-8019, USA*
²*Department of Physics, Royal Holloway, University of London, Egham, Surrey,
TW20 0EX, UK*

³*Department of Physics and Astronomy, University of California, Irvine,
CA 92697, USA*

Philip Warren Anderson was a pioneering theoretical physicist whose work fundamentally shaped our understanding of complex systems. Anderson received the Nobel Prize in Physics in 1977 for his groundbreaking research on localization and magnetism, yet he did so much more. His work on magnetism included antiferromagnetism, superexchange, the Kondo problem and local magnetic moments in metals. Anderson pointed out the importance of disorder through his work on localization, non-crystalline solids and spin glasses. In superconductivity, he is known for the dirty superconductor theorem, showing the gauge-invariance of the Bardeen–Cooper–Schrieffer theory, his study of flux creep and his collaboration with an experimentalist that led to the experimental realization of the Josephson effect. Anderson’s resonating valence bond theory may yet play an important role in high-temperature superconductivity. Anderson was also fascinated by broken symmetry, and he laid the theoretical groundwork for what is now known as the Anderson–Higgs mechanism, showing how gauge bosons can acquire mass—an insight that played a foundational role in the Standard Model of particle physics. In his seminal ‘More is different’ paper, Anderson argued that the collective emergent phenomena that arise in complex interacting systems cannot be deduced from their fundamental parts. Anderson’s legacy endures not only through the lasting impact of his scientific work but also through his influence on generations of physicists who continue to explore the rich landscape of collective behaviour in nature.

*Email: cyu@uci.edu

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<https://doi.org/10.1098/rsbm.2025.0029>

BIOGRAPHICAL SKETCH

Early years 1923–1949

Philip Warren Anderson ('Phil') was born on 13 December 1923, in Indianapolis, Indiana; he grew up in Urbana, Illinois, where his father, Harry W. Anderson, was a professor of plant pathology at the University of Illinois (UIUC). His paternal grandfather was a fire and brimstone preacher who later turned to farming. Phil's maternal grandfather was a professor of mathematics at Wabash College (Indiana), where his maternal uncle, a Rhodes scholar, was later on the faculty (Bernstein 1984). Phil's mother, Elsie O. Anderson ('Bodie'), was a formidable woman who had great plans for Phil. In later years Phil said that his older sister, Eleanor Grace Maass ('Gracie'), should have received similar attention as she too was very bright. Phil's daughter, Susan, notes that when Bodie learned Harvard required two years of Latin (Bernstein 1984), 'she exerted her considerable magnetism' to have the chairman of the UIUC Classics Department tutor Phil (Bernstein 1984), and that without her 'determined support and encouragement, he would have never made it to Harvard!'

Phil's parents belonged to a warm group of friends known as the 'Saturday Hikers'; some of his fondest childhood memories were of their outdoor activities together (31)*. The group was quite politically conscious with a sense of foreboding about global pre-World War II events. As a result, Phil retained strong political convictions throughout his life. In 1937, during his father's sabbatical, Phil spent an impressionable year in Europe, and much later he often spoke warmly about it.

In Urbana, Phil attended University High School, where a maths teacher, Miles Hartley, was one of the few who challenged Phil intellectually. Subsequently Phil headed to Harvard in 1940 on a National Scholarship, intending to major in mathematics. In a letter responding to Harvard's request for a profile of his son, Harry Anderson describes Phil as an 'even-tempered boy, tolerant of others' opinions but likely to defend his own stubbornly ... He is not at ease with people who do not interest him' (Zangwill 2023). The subsequent entry of the USA into the World War II shortened Phil's college years; he graduated with a degree in 'electronic physics' in 1943 and built antennas at the Naval Research Laboratory (NRL). This experience left him with a lasting admiration for Bell Labs engineers. While at the NRL, Phil acquired a quantum mechanics textbook from a colleague as collateral for money owed, and he eventually kept it.

After the War, Phil returned to Harvard to pursue a PhD in physics. In addition to his doctoral research, Phil enjoyed doing puzzles and singing with friends, including Tom Lehrer, who later became famous for his sardonic songs. While home visiting his parents in Urbana, Phil met Joyce Gothwaite. They married shortly afterwards and a daughter, Susan, soon followed. As Ravin Bhatt, a colleague at Bell and then Princeton, has noted (Bhatt 2021), 'Joyce was truly Phil's "rock" who kept him grounded, taking care of everything so that Phil could do his physics without worries'.

Inspired by John Van Vleck's lectures on solid-state physics, Phil decided to do his dissertation with him. Phil's thesis problem involved the observed line broadening in radio frequency spectra that could be studied due to wartime advances in electronics. Phil found that the techniques he was learning in quantum field theory were useful for his thesis research. His theoretical results were in excellent agreement with experiment. Phil successfully defended his thesis, 'The theory of pressure broadening of spectral lines in the microwave and infrared regions', on 19 January 1949, and later published his results in *Physical Review* (1); this paper continues to be cited.

*Numbers in this form refer to the bibliography at the end of the text.

Bell Labs 1949–1959

Van Vleck ('Van') taught Phil to have a deep respect for experiment, to identify key underlying concepts and to develop minimalist descriptive models (Zangwill 2023); many years later Phil passed along this philosophy to his many mentees under the mantra 'follow the data'. While pursuing his doctoral work, Phil learned of several experiments performed at Bell Labs, and he was determined to go there as a researcher (46); thanks to Van's efforts, in 1949 this happened. Whenever he reminisced about his times at Bell Labs, Phil had a twinkle in his eye. This research branch was originally intended to support its parent company, AT&T, to create a global communications system. However, it also developed into a centre of innovative thinking, particularly in the then nascent field of solid-state physics. 'At first sight,' noted the writer Arthur C. Clarke in the 1950s, 'when one comes upon it in its surprisingly rural setting ... [it] looks like a large and up-to-date factory, which in a sense it is. But it is a factory of ideas' (Clarke 1974; Gertner 2012). The scientific environment at Bell Labs had an incredible ambiance: it was a world of research unencumbered by bureaucracy that is seldom experienced today. Collaborations between researchers were encouraged, and chance interactions frequently occurred in the long corridors and in the stairwells. Phil adapted quickly to these surroundings, and many of his discoveries were connected to his close interaction with experimentalists.

When Phil arrived at Bell Labs in 1949, quantum mechanics was not yet 25 years old. In the mid 1930s, Eugene Wigner, at nearby Princeton, with his students John Bardeen, Conyers Herring and Fred Seitz, was establishing the field of solid-state physics. Shortly after World War II, Bardeen and Herring came to Bell Labs and Seitz went to Illinois. Both Illinois and Bell became powerhouses of solid-state physics in the USA. At Bell, Phil's mentors were Gregory Wannier, Conyers Herring and Charles Kittel, theorists roughly 10 years older than him, who introduced him to magnetism, phase transitions and current research developments. In early 1956 the theorists formed their own department with postdoctoral and summer visitor programmes. It was an extraordinary centre of intellectual activity, and Phil quickly became one of its central figures. He had a very interactive style, constantly sharing his ideas as they were developing. Morning coffees and regular group lunches were always very animated affairs with lots of lively, sometimes heated, discussions. For young aspiring researchers, these were wonderful opportunities to see physics evolving in real time!

At Bell, Phil transformed rapidly from a novice to a senior figure in condensed matter physics. Later he always said that his early years studying magnetism gave him the grounding and the flexibility to move to other areas (35). This was a period of tremendous research productivity for Phil; here we provide just a flavour of his work with more discussion to follow. Phil's detailed studies of antiferromagnetism led him to broken symmetry, a deep concept in physics with relevance well beyond the materials that inspired its original study. His interactions with experimentalist Bernd Matthias led him to explain how electrons form magnetic moments in alloys (10), part of the work later cited by the Nobel Prize committee. When Bell Labs expanded into low temperature research, Phil played key roles in the areas of superconductivity and superfluidity. Furthermore, his study of broken symmetry in the presence of long-range forces resulted in the Anderson–Higgs mechanism in particle physics. Inspired by George Feher's experiments on doped semiconductors, Phil found that disorder in materials could lead to new concepts rather than just being an inconvenient nuisance. For example, Phil realized that disorder in metals could 'localize' electron waves (4), transforming them into insulators, a process now called 'Anderson localization'; this work played a central role in his Nobel citation. Measurements indicating low-temperature frozen random spin states, rather than conventional spin ordering, in a class of disordered magnetic

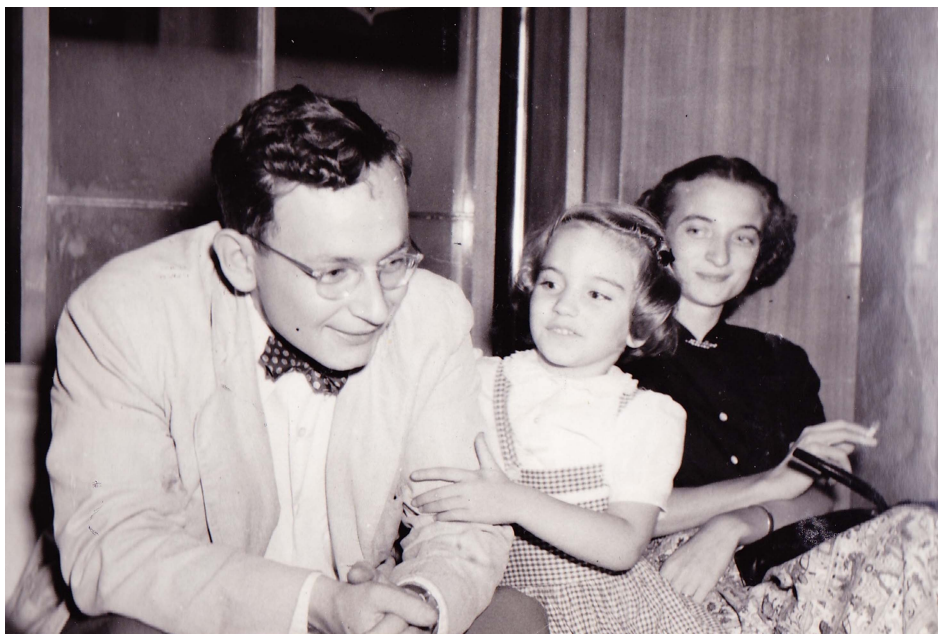


Figure 1. Phil and Joyce Anderson with their daughter Susan in Japan, 1951. (Courtesy, Susan Anderson.).

materials, now known as spin glasses, led Phil to appreciate that equilibrium statistical methods were insufficient to describe these systems (29). The approaches that his studies launched led to methods in combinatorial optimization that are used in very large scale integrated chip design.

In the 1950s, the Bell Labs management realized that their scientists would benefit from research sabbaticals away from the labs. Phil took full advantage of this freedom, and he would later claim that it was through his trips abroad that he was first appreciated within the academic research community (47). In 1953–1954, Phil was invited by Ryogo Kubo at the University of Tokyo for a sabbatical stay (46). The Anderson family sailed across the Pacific for a six-month visit (figure 1). Japan was still recovering from World War II, and large parts of Tokyo had yet to be rebuilt. Phil attended the 1953 International Conference in Theoretical Physics in Tokyo and Kyoto, his first experience on the international stage; here he made several acquaintances that would influence his later career, including Nevill Mott. Phil and Kubo had adjoining offices on the Hongo campus of the University of Tokyo, and regularly discussed their ideas on magnetism, electron spin resonance and statistical mechanics. During this stay, Phil also learned to play the Japanese game of Go, which became a lifetime pastime; he eventually attained the rank of first-dan master, and in 2007 he received a lifetime achievement award from the Nihon Ki-in, Japan's Go association (Brinkman *et al.* 2020). Later in life, Phil and Kubo would each jokingly claim that they were responsible for discovering the other one. Phil would also proudly recall pulling Kubo out of his office after he had become unconscious due to a gas leak.

Cambridge and England 1959–1975

In 1959 Phil was invited to a conference on magnetism held at Brasenose College, Oxford. There he learned about Jacques Friedel and Andrei Blandin's ideas on magnetic moment formation in metals, an approach that Phil would later transform into Anderson's local moment model (10). During this trip, interest grew in bringing Phil to England for an extended stay (Chandra, Coleman and Sondhi 2002). In 1961–1962, Phil was invited by Brian Pippard to spend a year in Cambridge. Phil lectured on solid state physics, many-body theory and superconductivity in a course attended by a beginning graduate student, Brian Josephson. After one such class, Josephson showed Phil his calculations of Cooper pair tunnelling, work that heralded the discovery of the Josephson effect for which Josephson would be awarded a Nobel Prize in 1973. It is a testimony to Phil's character that he always gave Josephson full credit for the discovery (21). Brian Josephson warmly remembers the many discussions they had together, noting 'one amusing thing was he couldn't be bothered to get equations exactly right, so had a convention whereby π and i were considered equal to one so they could be omitted from the equations!'.

Phil's sabbatical year went sufficiently well that Cambridge colleague Volker Heine recalls 'I can say that Mott and Pippard were keen to have Phil here half-time, shared with Bell Labs, more than anyone else full-time', and thus Phil became a part-time professor there from 1967 to 1975. This was an extraordinarily productive time for Phil. Concurrently he developed his philosophy of 'more is different', in which he argued that science is hierarchical, with new emergent principles to be found at every level of complexity. T. V. Ramakrishnan, a long-time friend and collaborator, writes (Ramakrishnan 2020): 'It awoke us to the reality of emergence, at a stage when 'real science' was equated with reductionism.' During his tenure at Cambridge, Phil mentored several doctoral students, visitors and postdocs, including Duncan Haldane, Michael Cross, John Inkson, Richard Palmer, David Bullet, Gideon Yuval, Ali Alpar and John Armitage, Erio Tosatti, Dennis Newns and Patrick Fazekas. Erio recalls: 'When Phil returned from the US, it felt like a ray of sun ... Interactions with Phil were, in everybody's opinion, a special experience—treasured by some, feared by others. Despite his kindness and human concern for everyone young and in any way helpless, Phil was generally a cryptic communicator, for some a mumbler, not easy to understand. If you, like myself, belonged to the first type of people, it was enough to listen to him for a quarter of an hour, to become instilled with so many ideas and insights to keep you busy for weeks and months.'

Phil's stay at Cambridge led to major progress across a diverse range of topics from neutron stars to spin glasses, while he also wrote the text *Concepts in solids* (16), based on his graduate lectures. With Yuval, Phil developed a new renormalization group approach for the physics of magnetic ions in metals known as the 'Kondo problem'. He worked on neutron stars and charge density waves with Alpar, Palmer and Tosatti. With Haldane, Phil developed early theories of valence fluctuations in solids; he worked on superfluid Helium-3 with Cross; and with Fazekas, Phil developed the concept of spin liquids, which would later become the basis of his theory of high-temperature superconductivity. A particularly notable collaboration developed with his colleague Sam Edwards on Saturday mornings. At that time, Edwards was chair of the Science Research Council, a UK funding body, and only returned to Cambridge on weekends. Phil and Edwards met every Saturday morning, developing a theory of spin freezing in random magnets called spin glasses. Concurrently Phil and his Cambridge colleague Volker Heine changed the name of their group from Solid State Theory to Theory of Condensed Matter to better reflect the inclusion of fluids, disordered systems, and more complex many-body phenomena; this nomenclature is now used everywhere.



Figure 2. Phil Anderson (left) with students Richard Palmer (behind Phil), Ann Eggington (right of Phil) and others on an excursion to Puffin Island as part of the St Andrews 1974 School on Low Temperature Physics. (Photo courtesy of Ann Eggington.).

Many researchers had some of their most memorable interactions with Phil outside the Cavendish lab. Volker and Erio recall that Phil would always eat a pub lunch with colleagues, students and postdocs, providing an opportunity for regular scientific and cultural interactions. Phil and Joyce Anderson were also wonderful hosts, and many fondly remember the parties they held in Cambridge during this period. In 1973 Phil and Joyce bought a holiday cottage in Port Isaac, Cornwall; postdocs and visitors were often invited to visit them there. Physics conferences also provided opportunities to spend time with Phil in a more relaxed setting.. One such memorable occasion occurred at the 1974 August Summer School on Low Temperature Physics, where the recent discovery of superfluidity in Helium-3 was discussed. The workshop took place in St Andrews in Scotland. Ann Eggington, conference attendee, recalled an excursion with Phil there (see [figure 2](#)): ‘We all set off to a boat trip to Puffin Island. The weather was agitated and the captain would not unmoor, seeing us as a human cargo of dubious resilience to the rough sea. As it happened, the captain’s name was Anderson. For Erio and I it was an easy game to ask Phil Anderson to confront Captain Anderson and guarantee that we would be OK—and it worked!’

Princeton 1975 onward

After eight years of feeling like tourists in both the British and American cultures, ‘with no really satisfactory role in either’, Phil and Joyce returned to the USA ([31](#)). Phil traded his part-time appointment at Cambridge for a part-time position as the Joseph Henry Professor of

Physics at Princeton University in the autumn of 1975, becoming full time at Princeton from 1984 to 1996, when he became professor emeritus. His new position allowed him to continue his work at Bell Labs, while establishing a centre for condensed matter at Princeton University. Phil's arrival there quickly nucleated a buzz of research activity: new students eagerly lined up to work with him, including Carol Morgan Pond, Daniel Stein, Henry Greenside and Albert Chang, joining Richard Palmer, Ali Alpar and Duncan Haldane, who travelled with him from Cambridge. James Sethna, Khandker Muttalib, Clare Yu, Gabriel Kotliar, Piers Coleman, Yaotian Fu, Al Kriman and Jerry Tesauro were among a subsequent group of students; a later set included Ted Hsu, Joe Wheatley, Zou Zhou, Jonathan Yedida, Philip Casey, Charles Stafford, Steve Strong and visitors Ganapathy Baskaran, Premi Chandra, Benoit Doucot, Antoine Georges, Ido Kanter and Shoudan Liang. There was much to learn from Phil. Ganapathy Baskaran notes that '[o]n several occasions, Anderson brought out deep meanings in ordinary sounding seminar talks and pleasantly surprised the speaker and the audience'.

Phil cared deeply about the young researchers in his charge. However, communicating with Phil was difficult, which made working with him a challenge. 'Phil was known ... as a Delphic Oracle, given his tendency to make cryptic and puzzling remarks when discussing a physics problem ... they often seemed mysterious at the time or else totally off the subject', notes Daniel Stein. 'But then, weeks later, it would suddenly dawn on me what he meant ... Once understood it always turned out to be insightful, relevant and deep.' James Sethna recalls that 'posed with a mystery or a challenge, Phil would invent the most interesting and insightful possible explanation'. He certainly had an unconventional approach. Clare Yu remembers a time when Phil was particularly exasperated with her and said, '[t]heoretical physics isn't doing calculations. It's setting up the problem so that any fool could do the calculation' (Chandra *et al.* 2015). Gabriel Kotliar shares that 'Phil was an unusual PhD advisor ... Pursuing hard problems without guaranteed success, together with trusting with some skepticism intuitive reasoning and creative methodologies was Phil's real lesson at the end, but ... it took some time to sink in'.

In October 1977 an early morning phone call from Stockholm informed Phil, reputedly brought in from his garden, that he had won the Nobel Prize for his work on electrons in disordered materials and his local moment theory of magnetism. Phil shared the prize with his doctoral advisor, John Van Vleck, and with Nevill Mott, his old friend from Cambridge (31). The acclaim, honour and attention of a Nobel Prize distracts many a researcher, but within a month of the festivities in Stockholm, Phil was back to commuting between his fledgling group at Princeton and his colleagues at Bell Labs. Indeed, in the following years, Phil and three collaborators resolved several issues related to Phil's prize-winning work on electron localization, leading to a publication in 1979 (33); the authors became known as the 'Gang of Four', a reference to four political defendants in a trial in China at the time. The paper ignited renewed interest in the field, and a slew of theoretical and experimental papers followed.

Phil's deep curiosity and passion for physics was undiminished by his many laurels and subsequent commitments. Here we give a flavour of his later adventures. Motivated by several experimental developments, Phil continued to work on various forms of magnetism in the 1980s; he also applied key concepts of spin glasses to combinatorial optimization and nondeterministic polynomial-time (NP) completeness. In 1983, Phil published a graduate textbook, *Basic notions of condensed matter physics* (37), combining his unique perspective of key ideas in the field with a selection of important reprints. The discovery of high-temperature superconductivity in the late 1980s remained a focus of Phil's attention for the remainder of his life. Ten years later, he published another book, *A career in theoretical physics*, consisting of reprints of his selected articles that are not easily accessible (42). In 2011, Phil published



Figure 3. Phil Anderson at Jadwin Hall, Princeton, 2011. (Photo courtesy Ganapathy Baskaran.).

his last book, *More and different: notes from a thoughtful curmudgeon* (45); the title is a play on that of his famous 1972 *Science* article, ‘More is different’ (25), which refuted the reductionist approach to science by noting that unexpected emergent phenomena can come from interactions between simple objects. The book is a collection of his non-technical writings, including essays, personal recollections and book reviews, giving a window into his thoughts and opinions about a broad range of topics. Phil’s daughter Susan notes that her father had a tremendous sense of fun and that ‘his love of the odd and the eccentric led to so many of his diverse interests’. She recalls that “‘higgledy-piggledy” was a favorite descriptor’.

In 1984 Phil retired from Bell Labs. After he became an emeritus professor at Princeton in 1996 (see figure 3), he continued to be an inspiring presence in the department. ‘Being Phil’s colleague for the past quarter century—when he was already a legend—was an honor in itself’, says Shivaji Sondhi, who was a faculty colleague at Princeton (Zandonella 2013). ‘My experience of him was of a man of wide learning well beyond physics, broad interests across science, enormous creativity and an extraordinary capacity—almost literally to the very end—to get up and think about important problems in physics.’ In 2013 Phil’s ninetieth birthday was celebrated with a weekend workshop that resulted in a book, *PWA90: a lifetime of emergence* (Chandra *et al.* 2015); Phil sat in the front row and asked questions of almost every speaker. ‘There are very few people in condensed matter physics who have not been influenced by Phil’s ideas’, states Anthony Leggett (FRS 1980), a professor of physics at the University of Illinois at Urbana-Champaign, who received the 2003 Nobel Prize in Physics (Zandonella 2013); ‘Even when he turned out to be wrong, he was influential because he got people to think in new directions.’

Over the course of his career, Phil was a mentor and an inspiration to many young researchers who themselves went on to make serious scientific contributions. In 2016 one of Phil’s former students and later a Princeton professor, Duncan Haldane, was awarded the

Nobel Prize in Physics. Commenting on his doctoral days with Phil, Duncan notes ([Zandonella 2013](#)): ‘I had the great fortune to have had him as my mentor when I was a graduate student. I would regularly meet him to talk about the problem he had given me to work on, but instead he would tell me about the things he was thinking about that day, and seeing his thought process was an amazing lesson in how to think about problems that decisively shaped my future career. What a mentor!’

Bell Labs, Aspen and Santa Fe

The demise of Bell Labs was heartbreaking for Phil: he took it personally as he had played a key role in building its international reputation. Opinionated as always, Phil often said that Bell was ‘extraordinarily poor at economically exploiting its technology’, and he felt that ‘if managed through the post-’84 crisis with the flexibility and intelligence exhibited in those early days ... it might still be with us’ (46). Phil played important parts in two other research centres, the Aspen Center for Physics (ACP) and the Santa Fe Institute, both located in the American West.

The ACP, originally a satellite of the Aspen Institute, became an independent entity in 1962. Initially founded by high-energy physicists, Phil played a major role in broadening its scope to include condensed matter workshops. Phil first came to the ACP in the summer of 1975, and he would subsequently return for a total of 22 summers, even serving as chair of its Board of Trustees (1982–1986). It was at the ACP that Phil worked with David Pines, Gordon Baym and others to apply concepts of condensed matter theory to astrophysical phenomena in neutron stars. In 2000 the ACP held a winter workshop honouring Phil’s scientific contribution; it resulted in a collection, *More is different: fifty years of condensed matter physics* ([Bhatt & Ong 1984](#)).

The Santa Fe Institute (SFI) was started in 1974 to encourage the flow of ideas between traditionally disparate fields. Phil was one of the interdisciplinary scientists who founded the SFI; he later became an external professor and served as a vice-chair of its Science Board. Phil and Nobel economist Kenneth Arrow led SFI workshops that brought together economists with natural scientists.

Political and cultural activities

Phil grew up amidst much political discussion, and he was not afraid to stand up for his beliefs. He often recounted how he was one of the few Bell Labs scientists who refused to answer a questionnaire about his political views during the McCarthy period; however, he admitted that Joyce was worried about possible consequences even though she shared his opinions. Later in life, Phil used the visibility of his Nobel Prize to take public stands. For example, he signed letters protesting the incarceration of the Russian dissident physicist Yuri Orlov (1978), endorsing a Comprehensive Test Ban Treaty (1999) and opposing the Iraq War (2003) ([Zangwill 2023](#)). Phil was particularly proud of his opposition to the Strategic Defense Initiative, colloquially dubbed ‘Star Wars’. He wrote ‘I happened to be in a position to be caught up in the campaign against “Star Wars” very early (summer ’83) and wrote, spoke and testified repeatedly, with my finest moment a debate with Secretary George Schultz in the *Princeton Alumni Weekly*, reprinted in *Le Monde* in 1987’ ([Zangwill 2023](#)) (31). In private discussions Phil often nudged colleagues, particularly young researchers, to develop opinions and to be ready to defend them.

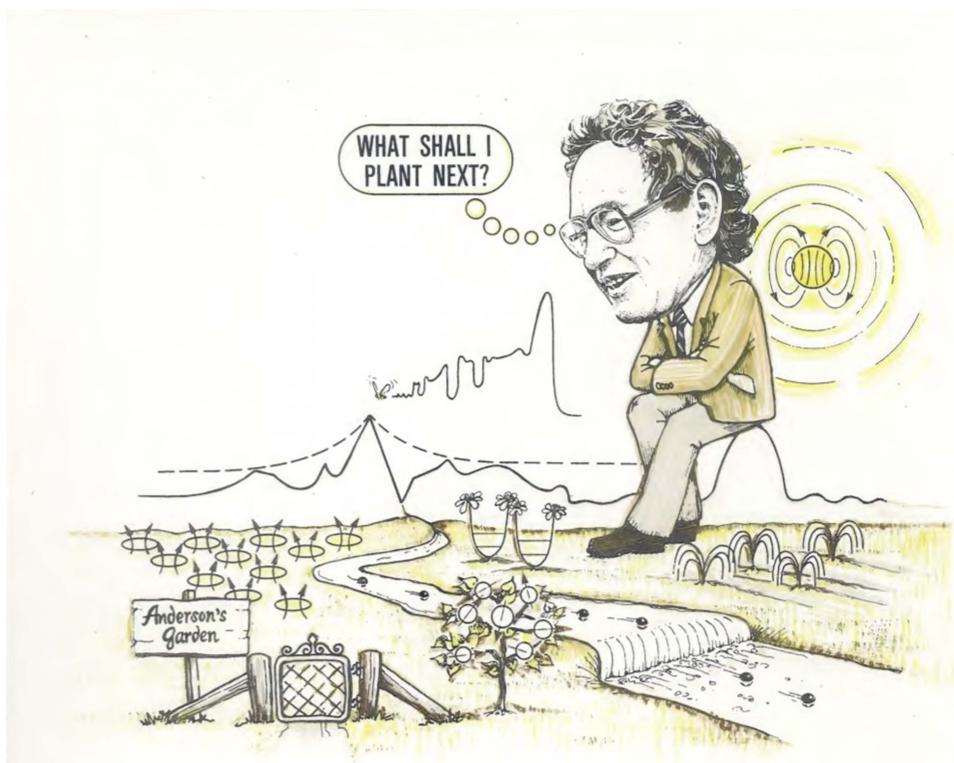


Figure 4. ‘Anderson’s Garden’, a schematic presented to Phil on the occasion of his sixtieth birthday, illustrating his garden of scientific accomplishments; Phil was an avid gardener, both of plants and of ideas. A flux lattice in a superconductor is on the left, on the right is a lattice of vortices in a superfluid. The mountain range in the background is presumably a pulsar ‘glitch’. Phil proudly hung this drawing on the wall of his Princeton office alongside photographs of Joyce and of the Russian physicist Lev Landau. (Artist unknown, reprinted from [Chandra et al. 2015](#).)

In addition to his scientific adventures, Phil was well read on a variety of subjects; he always relished a good argument about history, economics, and politics (and he did not give in easily!). In the latter part of his life, Phil wrote several non-technical pieces commissioned by his friend Andrew Robinson of the *Times Higher Education Supplement*. ‘My dream of giving up physics for writing, however,’ wrote Phil in 2011 (47), ‘never materialized; physics continues to dominate my professional life.’ Phil himself was a living refutation of the standard notion that achievement in physics is age-restricted; he wrote ‘in my experience the cliché is wrong, wrong, wrong’ and ‘to my surprise, physics has remained exciting and wholly absorbing as I age, and while I love to write, that occupation has always been secondary’ (47).

Phil remained active and opinionated about physics well into his ninth decade. In 2006 a statistical analysis ([Soler 2006](#)) gave Phil its highest ‘creative index’, naming him the ‘world’s most creative physicist’; always competitive, Phil was thrilled to be followed by particle theorists Steven Weinberg and Edward Witten in this study. Phil was curious to the very end. He passed away on 29 March 2020. According to his daughter Susan, one of the last books Phil was reading was *Birth of a theorem: a mathematical adventure* by Cedric Villani ([Villani 2012](#)).

11/30/63 Another impossible experiment: the
neutrino ~~Josephson~~ Mossbauer effect.
Idea: take a deeplying donor or
acceptor state, caused by a neighboring
element, $\Delta Z = \pm 1$. Examples: Cu_{64} in
 ZnO or ZnF_2 , etc. As^{73} in GeO_2 ;
 I^{125} in ~~Pb~~ Te . $CdTe$ or something of
the sort. Au^{199} in $HgCl_2$. If the

Figure 5. 'Another impossible experiment'. Entry from Phil Anderson's 1963 notebook on 30 November 1963 discussing the possibility of a neutrino Mossbauer effect (17).

SELECTED SCIENTIFIC WORK

Overview

Throughout his academic life, Phil's insatiable curiosity led him to ask questions that often resulted in new fields of research. Indeed, on the occasion of his sixtieth birthday, Phil was presented with a schematic garden of scientific flora that he had planted intellectually (see figure 4). He wrote copiously about his impressions of talks, discussions and papers, and most importantly on his many creative ideas. His Bell Labs notebooks, currently housed in the Firestone Library of Princeton University, present a window into his original thinking patterns (17). There are entries under the heading 'impossible experiments', such as the 'neutrino Mossbauer effect' displayed in figure 5, where Phil brainstormed about novel kinds of measurements; also there are instances where he commented 'Great idea flopped' and then he moved on to other things. Here we present a flavour of his key scientific accomplishments.

One of Phil's pioneering contributions to physics was in furthering the concept of 'broken symmetry', an idea originated by the Russian physicist, Lev Landau. Symmetry is a cherished principle in physics; thus a fluid, such as water, has continuous translational and rotational symmetry because its properties are independent of position or the direction in which they are observed. However, when water freezes, its atoms crystallize into a regularly spaced lattice acquiring discrete rather than translational and rotational symmetries, a feature responsible for the shape of a snowflake. Thus crystallization 'breaks' the symmetries of the fluid, but in return, it develops a beautiful regularity and forms a new state of matter, a solid.

Phil extensively used the concept of broken symmetry to understand new phases of matter, including magnetism, superconductivity and superfluidity, and he further extended his insights to particle physics, where his discovery of the Anderson–Higgs mechanism that gives mass to gauge bosons is central to the modern understanding of elementary particle physics and the early universe.

Anderson's magnetic life

The spin angular momentum of the electron plays a central role in magnetism. The spin of an electron is quantized to be either ‘up’ or ‘down’, denoted by $\uparrow$ or $\downarrow$. Ferromagnetism, seen in iron, involves the parallel orientation of electron spins, denoted as $(\uparrow\uparrow\uparrow\uparrow)$, but in an antiferromagnet, electrons at neighbouring atoms alternate between ‘up’ and ‘down’ directions, denoted by $(\uparrow\downarrow\uparrow\downarrow)$, and the magnetic fields they produce cancel, leading to no net magnetization. Quantum mechanics causes the spins in an antiferromagnet to fluctuate between configurations, $(\uparrow\downarrow) \rightleftharpoons (\downarrow\uparrow)$, which could melt the order. Why, then, do materials pick a particular antiferromagnetic arrangement? Phil showed that the strength of these quantum fluctuations depends on dimensionality (3). The fluctuations become so strong in one-dimensional chains that they melt the antiferromagnetic order, but they become weak enough in higher dimensions to allow antiferromagnetism to survive, albeit with a reduced magnitude (3).

In antiferromagnets such as MnO, Phil helped clarify how two magnetic atoms can develop an antiparallel spin alignment, even when they are separated by a non-magnetic atom, such as oxygen, and are thus too far apart to interact via direct exchange. This interaction was termed superexchange. In one of his earliest works at Bell Labs, Phil showed that, when electrons exchange their spins via an intermediate non-magnetic ion, they form a high-energy virtual state with two antiparallel electron spins in the same orbital (2). These virtual fluctuations stabilize the antiferromagnetic configurations of the electrons on the magnetic atoms. Phil subsequently showed that the virtual charge fluctuations responsible for antiferromagnetism do not require an intermediate non-magnetic atom (7), thus broadening the meaning of superexchange. Key to this later work was the adoption of Mott’s conceptualization of the Coulomb interaction as an onsite repulsion energy (Mott 1949), which Phil labelled ‘ U ’, and the formulation of his ideas using a second-quantized formalism.

Phil’s local magnetic moment model (10), cited prominently by the Nobel Prize committee (31), addresses the question of how a localized electron magnetic moment survives in a metal. Phil’s model considered an atomic impurity with a localized electron orbital, such as a transition metal atom with a d-orbital immersed in a metal. Two key features of the model are the hybridization between the d-orbital and the conduction sea, allowing electrons to tunnel in and out of the d-orbital, and the introduction of the onsite U from his earlier work. He demonstrated that in the magnetic state, a single electron spin occupies the localized orbital, while additional electrons are blocked from occupying the orbital by the onsite Coulomb repulsion U .

The Kondo problem

Phil’s 1961 paper on moment formation left open the question of how a magnetic moment in a metal behaves at low temperatures, when quantum fluctuations become important. This innocent question blossomed into a major theoretical challenge known as the Kondo problem. Most electrical resistance in metals is caused by the scattering of electrons from thermal vibrations

of atoms. Normally, as these vibrations subside upon cooling, the resistivity decreases. However, in the 1930s, experiments found that the resistivity of copper, gold and silver reaches a minimum, and then starts to rise upon further cooling. In 1964 Myriam Sarachik at Bell Labs showed experimentally that the mysterious ‘resistance minimum’ (Sarachik *et al.* 1964) is caused by electrons scattering from magnetic iron impurities.

Around this time, the Japanese physicist Jun Kondo used perturbation theory to study the scattering of electrons off iron moments. He used a model of spin exchange between conduction electrons and a localized d-electron, a model that is contained in Anderson’s local moment model. Kondo showed that the predicted resistance has a minimum (Kondo 1964), but there was a problem: below a certain temperature, the ‘Kondo temperature’, he found that magnetic scattering becomes so strong that his perturbation theory was no longer valid. What happens at lower temperatures? Nobody knew. This question became known as the ‘Kondo problem’, and it became a cause célèbre.

The solution to the Kondo problem had to await the development of a new tool called the ‘renormalization group’ that had entered particle and statistical physics in the 1960s and 1970s. Phil’s team, consisting of his Cambridge student Gideon Yuval and Bell Labs colleague Don Hamann, successfully applied the renormalization group to the Kondo problem (22, 23) by mapping the sequence of spin flips in time onto a classical 1D Ising model with long-range interactions. This work convincingly demonstrated that, at low temperatures, the local moment forms a singlet with effectively a single conduction electron spin and becomes non-magnetic, i.e. the conduction electrons completely screen the magnetic moments.

The influence of these new ideas ranged far and wide, establishing the importance of renormalization group methods in quantum systems, opening a new path forward for theoretical work. It influenced Kenneth Wilson in the development of his numerical renormalization group approach (Wilson 1975), the basis of modern density-matrix renormalization group approaches to quantum problems (White 1998). The Anderson–Yuval–Hamann approach was later adapted by Kosterlitz and Thouless (Kosterlitz & Thouless 1973) to understand the interaction between vortices in a two-dimensional superfluid, leading to the famous Berezinskii–Kosterlitz–Thouless phase transition, for which Kosterlitz and Thouless were awarded the Nobel Prize in 2016.

Disorder-induced physics

Before Phil came along, most of the work in solid-state physics had centred around ordered, crystalline materials. Phil pioneered the idea that disorder leads to new physics and should not be thought of as merely a perturbation or an annoyance. As we describe below, this can be seen in his seminal works on localization, local magnetic moments (see above), glasses and spin glasses.

Localization

As far as electrical conduction is concerned, there are two basic types of materials: insulators and metals. In metals, electrons flow in response to an applied electric field (or voltage), giving rise to an electric current, but in insulators electrons are not able to flow and conduct electricity in response to an applied voltage.

By 1958 there was a good understanding of how electrons flow in crystalline metals, where the atoms are arranged in an orderly fashion. While it was known that disorder in a crystal, e.g.

impurities or atoms displaced from their lattice sites, would lead to increased scattering of moving electrons and increased electrical resistance, it was generally believed that the electrons would continue to diffuse through the lattice, which would thus remain metallic. However, in a landmark 1958 paper, entitled ‘Absence of diffusion in certain random lattices’ (4), Phil showed that, in the presence of enough disorder, electrons become localized, or confined, to a particular region of the material so that they no longer conduct, resulting in an insulator.

His work defined an entirely new problem, and both his approach and conclusion are testimonies to his originality and creative insight. His 1958 localization paper (4) was cited as one of the reasons for awarding him the Nobel Prize. Yet, this work was largely unappreciated (even by the author) and it would be many years before Phil returned to the problem.

In 1979 Phil revisited the problem of localization. In a landmark ‘Gang of Four’ paper (33), the authors considered disordered metals in one, two and three dimensions. They used a scaling theory to show that one- and two-dimensional systems would become insulators for infinitesimal amounts of disorder. This work has had a wide influence in science and is one of the most cited papers in *Physical Review Letters*.

The original ideas of Anderson localization were for disordered systems in which interactions between electrons are ignored (4). Phil presented qualitative arguments that such localization should survive weak short-range interactions (34). The subsequent observation of metal-insulator transitions in several dilute two-dimensional electron and hole systems (Abrahams *et al.* 2001) was thus a surprise to the community, and the study of such disordered, interacting phases (in thermal equilibrium) remains active to this day (Lee & Ramakrishnan 1985; Giamarchi & Schulz 1988; Giamarchi 2003).

Localization is being actively investigated in the context of (super) cold atoms where the presence of a disordered potential and interactions can be carefully controlled. Localization has been experimentally observed in cold atom systems both in the absence of interactions (Billy *et al.* 2008; Roati *et al.* 2008) and in the presence of interactions (D’Errico *et al.* 2014). There is also interest in so-called many-body localization where a system of interacting electrons in a disordered potential is prepared in thermal equilibrium with a thermal bath, and then isolated from the bath and allowed to evolve quantum mechanically to see if the conductivity is zero or not (Gornyi *et al.* 2005; Basko *et al.* 2006; Abanin *et al.* 2019).

Two level systems

In 1971 Zeller and Pohl found that at temperatures below 1 K, insulating glassy (non-crystalline) materials, regardless of their chemical composition, exhibit a specific heat that is linear in temperature T and a thermal conductivity that goes as T^2 (Zeller & Pohl 1971). (Specific heat is indicative of the number of degrees of freedom that can be excited when the system absorbs heat. Thermal conductivity is a measure of how well the system conducts heat.)

In seminal papers, Anderson, Halperin and Varma (26) and, independently, W. A. Phillips (Phillips 1972) proposed that the thermal behaviour in glasses at low temperatures could be explained by so-called two-level systems (TLS). The basic idea is that an atom or group of atoms can sit more or less equally well in either of two configurations, i.e. in either of two minima of a double-well potential. At low temperatures, there is not enough thermal energy to hop over the barrier between the two wells, but quantum mechanically, the atom or group of atoms is able to go through the barrier, i.e. tunnel back and forth between the two configurations represented by the two minima. The system has two energy levels. In the TLS model, the energy difference between these two energy levels has a uniform or flat distribution up to a

few tens of degrees, resulting in a specific heat that is linear in temperature. Furthermore, the phonons carrying the heat scatter from the TLS, resulting in a thermal conductivity that is quadratic in temperature. Although the microscopic nature of the TLS remains a mystery in most cases, the model has been enormously successful in explaining a variety of both thermal and ultrasonic measurements. Indeed, by drawing an analogy between TLS and (nuclear) spins, many of the well-known nuclear magnetic resonance techniques have analogues when the magnetic field is replaced by a strain field (or an electric field if the TLS have electric dipole moments), e.g. phonon echoes in glasses are analogous to spin echoes.

Although Phil did not continue to work on TLS, the model and its implications live on in the present day. Indeed, currently, TLS are a focus of intense interest in the effort to build a quantum computer from superconducting and semiconducting qubits because TLS with electric dipole moments are an important source of noise and decoherence (Martinis *et al.* 2005), and must be dealt with if quantum computers are to become a reality.

Spin glasses

In 1975, Phil and Sam Edwards proposed the first model of spin glasses (29). They were inspired by experiments in which magnetic impurities, such as manganese atoms, were doped into a non-magnetic host such as copper. As these systems were cooled, they exhibited a transition into disordered magnetic states.

In ordered magnetic systems such as a ferromagnet or an antiferromagnet, the interactions between pairs of magnetic moments, or spins, are identical. However, in a spin glass, the interactions are random, leading to frozen, disordered configurations of spins at low temperatures. Phil and his collaborators introduced a number of important theoretical techniques to deal with the challenges that frozen-in randomness, known as quenched disorder, posed. These include the so-called ‘replica trick’ (29) and the Thouless–Anderson–Palmer equations (32). Many years later, two researchers who worked in the early stages of their careers with Phil (B. G. Kotliar as a graduate student and A. Georges as a postdoctoral fellow) built on these ideas to develop the dynamical mean field theory (Georges *et al.* 1996), a widely used framework for incorporating strong electron correlations in computational studies of quantum materials.

The impact of the concepts developed for spin glasses extends far beyond disordered magnets. One of the key concepts was frustration in which a spin cannot find an orientation that satisfies the demands of all the neighbouring spins. For example, one neighbour wants a spin to point up while another neighbour wants it to point down. Another key concept, also recognized in structural glasses (Goldstein 1969), is the picture of an energy landscape where valleys, or minima, represent metastable states. Simulated annealing was developed as a way to find these local minima. When John Hopfield was developing his model of neural networks, Phil encouraged him to consider spin glasses as an analogue system where the spins represented neurons and the connections between neurons were represented by the random interactions between spins. Other applications include combinatorial optimization, content-addressable memories and, most recently, machine learning.

Superconductivity: a scientific love affair

Kamerlingh Onnes discovered superconductivity in 1911 when he cooled mercury and found that its electrical resistance suddenly vanished at a transition temperature of $T_c = 4.2$ K. It was not until 1957 that John Bardeen, Leon Cooper and Robert Schrieffer published their

microscopic theory of superconductivity. In the ‘BCS theory’, the superconducting wavefunction is written in terms of ‘Cooper pairs’, with each pair consisting of two electrons with opposite spin and opposite momenta. On the day in spring of 1957 when Phil first heard about BCS at a talk at Princeton by David Pines, it was ‘love at first sight’ (44). On the way back to Bell Labs, he had a eureka moment that linked BCS theory to magnetism. Using a ‘pseudo-spin’ reformulation of BCS, Phil was able to map the problem of superconductivity onto magnetism. This new analogy enabled him to confirm that BCS was gauge invariant and establish that the Coulomb repulsion between electrons in a superconductor is screened just as it is in a metal (5).

Phil’s reformulation of BCS had wide influence. By linking superconductivity and magnetism, the community took a cautious step closer to regarding the phase of the superconducting wavefunction as a palpable, detectable variable (with the caveats of gauge fixing). This emerging perspective would culminate in the discovery of the Anderson–Higgs mechanism (49) and the Josephson effect (15, 21).

Josephson effect and broken symmetry

As we described earlier, Brian Josephson was a young graduate student in Phil’s course when he came up with his Nobel Prize-winning ideas (15, 18) (Josephson 1962). Phil was probably among the first to appreciate Josephson’s ideas, and they had a profound influence on his evolving understanding of superconductivity and broken symmetry (21) (Chandra, Coleman and Sondhi 2002).

The Josephson effect arises in a tunnel junction between two superconductors. A tunnel junction involves a nanometre-thin insulating layer, usually formed from an oxide, sandwiched between two superconductors. Each superconductor has a coherent superconducting wavefunction consisting of superconducting electrons. Think of the wavefunction as a wave with an amplitude and a phase. If, as is usually the case, the two superconductors have different phases, then current will flow across the tunnel junction without any applied voltage drop, i.e. without any batteries! The current depends nonlinearly on the phase difference δ , and is proportional to $\sin \delta$. Josephson also predicted that if a voltage is applied across the junction, then the phase would vary in time.

When Phil returned to Bell Labs in August of 1962, he began to discuss with his colleague, John Rowell, the possibility of experimentally confirming Josephson’s effect, initiating a very close collaboration between experimentalist and theorist. In January 1963, when Rowell first tried the experiment, no supercurrent was observed. Rowell recalls that Phil realized overnight that ‘I had to make lower resistance junctions ... So I tried a tin-lead junction first, this was January 21st 1963 that I first saw a convincing Josephson current’ (Rowell 2012). The new experiment displayed currents with tremendous sensitivity to magnetic fields.

Their resulting paper had Phil as the first author (15) (Rowell 2021a,b). Phil and Rowell went on to propose and patent the use of superconducting quantum interference effects as a method for detecting minute magnetic fields. The modern realization of this idea is the (DC) superconducting quantum interference device (SQUID), which consists of a loop of superconducting wire with two Josephson junctions. Just as a wave passing through two slits in a wall produces constructive and destructive interference patterns, the superconducting wavefunction going through the two junctions leads to interference that is sensitive to the magnetic flux through the loop, creating an extremely sensitive magnetic field detector. Today, SQUIDS are used to detect the magnetic fields produced by electric currents in the brain and are the

leading candidate for quantum bits, or qubits, which are the basic element of a quantum computer (Levi 2009).

The Josephson effect showed that a superconductor prefers a smooth wavefunction with the same phase everywhere: if there are variations in the phase, then current flows to eliminate the phase difference, even with an insulating tunnel junction in the way (18, 21). This puzzled the community, and luminaries such as John Bardeen (McDonald 2001) initially opposed it, because it went against a belief that the phase of the quantum mechanical wavefunction is unmeasurable and therefore without physical consequences. The new insight was that the energy can be a function of the *gauge invariant* difference of phases (18)

$$E \sim \left(\vec{\nabla} \phi - \frac{2e}{\hbar} \vec{A} \right)^2 \Rightarrow -\cos \left(\phi_2 - \phi_1 - \frac{2e}{\hbar} \int_1^2 \vec{A} \cdot d\vec{\ell} \right), \quad (1)$$

where ϕ is the phase of the superconductor, while $\vec{A}$ is the electromagnetic vector potential; the left-hand side of the equation is the gauge invariant energy to twist the phase of a superconductor in the bulk that had been introduced by Ginzburg and Landau (Ginzburg & Landau 1950), whereas the right-hand side of the equation is Josephson's expression for the gauge invariant energy for two superconductors with a phase difference between their phases $\phi_2 - \phi_1$, separated by an insulating barrier. The important point was that the combination of the phases and the electromagnetic field $\vec{A}$ is gauge invariant. Josephson's results had a profound influence on Phil: he internalized them and realized their broader implications, not only for superconductors but also for broken gauge symmetry in particle physics (Chandra, Coleman and Sondhi 2002). As we will discuss shortly, it was this new perspective that allowed him, in the autumn of 1962, to propose the Anderson–Higgs effect (49).

A mile of dirty lead wire

Although superconductors involve a quantum mechanical phase coherence of electrons, they are unexpectedly robust against disorder. Phil often quoted Hendrik Casimir's remark that 'The remarkable thing is that electrons somehow manage to maintain a kind of order, whatever it may be, over a mile of dirty lead wire' (48). He recognized that the robustness of superconductivity against disorder results from time-reversal symmetry, the invariance of physics under the reversal of a trajectory. In his famous 'dirty superconductor theorem' paper, published in 1959 (8), he demonstrated that Cooper pairing survives without a reduction of T_c , so long as the disorder preserves time-reversal symmetry.

Another puzzle was how electron pairing in BCS theory could survive Coulomb repulsion. Lattice vibrations, or 'phonons', provide the pairing glue of Cooper pairs. BCS theory tacitly assumed that the electron–phonon attraction was big enough to overwhelm the Coulomb interaction, but did not provide a mechanism. In 1960, Pierre Morel, who was a French graduate student, and Phil recognized that the key to the puzzle lies in the very different time-scales associated with the two interactions. Electrostatic repulsion is instantaneous, but the electron–phonon interaction is 'retarded', because ions in a crystal respond much more slowly than electrons, so the deformation of the lattice created by a passing electron lingers long after it has passed by, which allows it to attract electrons long after the Coulomb repulsion has died away. Phil and Morel showed that the retarded part of the Coulomb repulsion is much reduced, and it is this reduction that makes superconductivity possible (12) (Tolmachev 1961).

Flux creep

Superconductors expel magnetic fields from their interiors if the fields are not too large. This is known as the Meissner effect. If the external field is too large, then superconductivity is destroyed in type I superconductors. However, as the field increases, type II superconductors admit larger fields in the form of magnetic vortices or magnetic flux lines. These magnetic filaments can be thought of as tiny tornadoes where there is electric current swirling instead of wind. The core of the vortex is basically a normal metal wire with normal (non-superconducting) electrons. As the field increases, more vortices are admitted and eventually the system becomes a normal metal when the vortices overlap. When electric current flows, these vortices are pushed sideways and, if they move, the normal electrons in their cores produce electrical resistance. Pinning a vortex prevents it from moving. Phil pointed out that it is not necessary to pin each and every vortex because, if the vortices are close enough to each other, they will move in 'flux bundles', a concept he introduced (13). Phil pointed out that the pinning of flux bundles prevents them from moving easily; this leads to 'flux creep'. Type II superconductors are used commercially to produce high magnetic fields, because they can carry large currents as long as the flux lines are effectively pinned. Magnetic resonance imaging machines used in the clinic are a prime example of an application of type II superconductors.

Resonating valence bonds

The chemist Linus Pauling had introduced the concept of a resonating valence bond in structures such as benzene molecules, and had actually suggested this as a basis for understanding the metallic state (Pauling 1953). Phil, working with postdoc Patrick Fazekas, now applied this concept, arguing that in certain frustrated two-dimensional magnetic insulators, such as a triangular lattice antiferromagnet, the ground-state would consist of a fluctuating liquid of spin singlets formed between neighbouring spins. They called it a 'resonating valence bond', or RVB, state (28).

This idea received very little attention until 1986, when the discovery of high-temperature superconductivity by Bednorz and Müller changed everything (Bednorz & Müller 1986). They found that doping strontium into insulating lanthanum cuprate yields a high-temperature superconductor. Insulating lanthanum cuprate is a type of Mott insulator, in which the strong Coulomb repulsion between electrons produces an insulator; that such a system should become a high-temperature (high T_c) superconductor upon doping was truly mind-boggling.

Upon hearing of the new discoveries, Phil had immediately started to wonder whether insulating lanthanum cuprate might be an RVB spin liquid with pre-paired electrons. No charge could move in the spin liquid, but, on doping with strontium, electrons removed from the liquid would create mobile vacancies, or holes, transforming the pre-paired state into a superconductor. Unlike conventional superconductors with Cooper pairs, Phil introduced the new idea that a pre-paired fluid of electrons was already present in the insulator. The resulting paper in *Science* is one of his most highly cited papers (40).

Surprisingly, Phil abandoned his idea of RVB superconductivity in the early 1990s, only to change his mind again in 2004 as it became increasingly clear that the idea may indeed contain a strong element of the as-yet undiscovered final theory of high- T_c (43). Indeed, early work by one of Phil's former students, Gabriel Kotliar (Kotliar 1988; Kotliar & Liu 1988), demonstrated that RVB theory predicts the d-wave pairing symmetry observed in high- T_c cuprate

superconductors. More generally, RVB theory seeded a new genre of research: quantum spin liquids (Balents 2010; Knolle & Moessner 2019) and it sparked a new interest in emergent gauge fields in quantum materials, a prominent area of current research (Sachdev 2016).

Superfluid helium-3

Sometime around 1960, physicists realized that BCS theory could be generalized to Cooper pairs of fermions with a finite angular momentum, and this led to the prediction that, at low temperatures, helium-3 atoms, which are fermions, would become a superfluid, a neutral fluid with zero viscosity. Like a molecule, Cooper pairs can have integer orbital angular momentum s-states ($\ell = 0$), p-states ($\ell = 1$) and d-states ($\ell = 2$).

In a paper with Brueckner, Soda and Morel, Phil predicted that helium-3 would become a d-wave or $\ell = 2$ superfluid at low temperatures (9). In a second paper, Phil and Morel extended the theory further to the p-wave case, in which the spins of the fermion pairs align to form a triplet. This led them to discover a magnetic superfluid ground-state (11).

Some 13 years later, Osheroff, Richardson, and Lee discovered that helium-3 becomes a superfluid below 2.7 mK; surprisingly, there are two superfluid phases that they called the 'A' and 'B' phases (Osheroff *et al.* 1972). It turns out that the helium-3 atoms do not pair in a d-state but in a p-state. Later analysis showed that the A-phase corresponds to the Anderson–Morel phase that they proposed in 1961; the B-phase corresponds to a state proposed in 1963 by Balian and Werthamer (Leggett 1975).

The Anderson–Higgs effect

In the early 1960s particle physicists were puzzled by the short range of the nuclear forces that hold protons and neutrons together in a nucleus. Yukawa and others had reasoned that these forces are mediated by the exchange of massive particles. On the other hand, theoretical considerations suggested that these exchange forces would be carried by nuclear analogues of the photon, called gauge bosons, and that this would inevitably result in massless particles with long-range nuclear forces. Since the forces of particle physics are short-ranged, this posed a conundrum. In a remarkable set of insights based on superconductivity, Phil proposed a way out (49) (Close, 2012; Witten 2015).

Phil realized that photons acquired a mass in superconductors, thereby making the electromagnetic force inside a superconductor short-ranged (6). A manifestation of this is the Meissner effect in which external magnetic fields decay exponentially at the surface of a superconductor, which can be viewed as a massive photon.

From his interactions with Brian Josephson as well as with Bell Lab visitors Robert Brout and Yoichi Nambu, Phil proposed a mechanism in which the short-range nuclear forces are mediated by subatomic gauge bosons that acquire mass in a kind of cosmic superconductor (Chandra, Coleman and Sondhi 2002), known today as the Higgs field after the British physicist Peter Higgs. Phil's seminal 1962 paper, 'Plasmons, gauge invariance and mass' (14), was prominently cited in a 1964 paper by Peter Higgs, which predicted the Higgs boson (49).

Two years later, a series of particle physicists, Peter Higgs, Robert Brout and François Englert, Tom Kibble and others, generalized the Anderson mechanism to a relativistic theory applicable to particle physics (Witten 2015). Both Higgs and Kibble mention Phil's work in their seminal papers. Peter Higgs and François Englert received the Nobel Prize for this work

in 2018. In a nod to Phil's achievements, physicists now refer to the mechanism by which gauge bosons acquire mass as the Anderson–Higgs effect.

Astrophysics: neutron stars

When stars undergo a supernova explosion, protons and electrons are crushed together by the recoil, leaving behind a small, dense core of neutrons known as a neutron star. According to M. Ali Alpar, one of Phil's former graduate students, 'Phil's interest in neutron stars started in 1967 with the discovery of pulsars by Jocelyn Bell, a student of Antony Hewish in the Cambridge Radio Astronomy group' (Alpar 2023). Jocelyn Bell had detected intermittent radio signals that occurred with amazing regularity. These pulses turned out to come from a rapidly rotating neutron star, termed a 'pulsar', that emits a beam of electromagnetic radiation like a lighthouse. We detect this radiation when the beam sweeps past the Earth. The discovery of pulsars was the first observation of neutron stars, an extreme form of matter that naturally attracted the attention of several solid-state theorists (Baym 2011).

Because neutrons, like electrons, are fermions, BCS theory could be applied to a superfluid of neutrons in neutron stars, and this fascinated Phil. He was particularly interested in observed 'pulsar glitches', temporal irregularities in the emitted radiation. In a series of papers, Phil and his collaborators made strong analogies between superfluid vortex dynamics in neutron stars and flux dynamics in type II superconductors. More specifically, they suggested that the observed pulsar glitches resulted from the sudden release of neutron vortex lines that were pinned by nuclei in the neutron star's inner crust (30, 36). Further work led to the concept of continuous thermal vortex creep in a pinning landscape, in analogy with flux creep (38, 39). Though Phil felt that these ideas 'ended up being right and probably even being proved out' (Chandra, Coleman and Sondhi 2002), the 'apathetic response to our work in the astrophysics community' may have led him to leave this area.

More is different: emergence

In the 1960s a prevailing philosophy in physics was reductionism—the idea that if you reduce everything to its smallest components, you could then reconstruct and understand everything. Phil disagreed strongly; in 1969 he gave a lecture at the University of California, San Diego (24), introducing a radically new perspective that he later published in a landmark *Science* article, 'More is different' (25). Phil argued that reductionism fails to take into account complexity, broken symmetry and length scales. Instead, he argued that science is hierarchical and that 'at each stage, entirely new laws, concepts and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one'. 'More is different' ends with a key assertion: 'Surely there are more levels of organization between human ethology and DNA than there are between DNA and quantum electrodynamics, and each level can require a whole new conceptual structure.'

Curiously, although the word 'emergence' does not appear in 'More is different', Phil's article contains several examples of how complexity gives rise to emergent properties, highlighting the importance of symmetry and the ways it can be broken in the thermodynamic limit. For example, we may know everything about a helium atom, but we would be hard pressed to predict superfluid helium from this knowledge. Phil dared to go far beyond examples from physics to touch on the social and biological sciences, where he suggested that DNA might be an example of an 'information bearing crystallinity' and discussed the possible connection

of life to the emergence of states of matter that develop ‘temporal regularity’. Over the years, ‘More is different’ has become the clarion call for the fundamental importance of complexity and emergence, exerting an enormous impact on research far beyond physics, including biology, complexity science, non-linear dynamics, economics, philosophy and the social sciences (Dosi & Roventini 2019; Strogatz *et al.* 2022; Stumpf 2022).

FINALE

In concluding this biographical memoir, we should like to quote from the citation of Philip Warren Anderson’s 1991 honorary doctorate from Rutgers University; it was written by one of his longtime friends and collaborators, Elihu Abrahams:

Phil Anderson, your remarkable insights into the quantum-mechanical foundations of the behavior of matter have transformed the main lines of thought and practice in modern solid state and condensed matter physics ... Your work shows that the most original and beautiful theoretical concepts arise from a deep understanding of the phenomena revealed in experimental laboratories. As the mentor of many junior colleagues who have themselves made outstanding contributions, you have inspired a generation of physicists who champion this dynamic relationship of theory and experiment. The profound discoveries you have made have been generated by your unique creative personality and confirm the place of science among the great achievements of the human spirit.

AWARDS AND RECOGNITION

- 1963 Member, American Academy of Arts and Sciences
- 1964 Oliver E. Buckley Prize in Condensed Matter Physics
- 1967 Fellow, National Academy of Sciences, USA
- 1975 Dannie Heineman Prize
- 1977 Nobel Prize in Physics
- 1978 Honorary Fellow, Jesus College, Cambridge
- 1978 Honorary Doctor of Science, University of Illinois, Urbana-Champaign
- 1980 Foreign Member, the Royal Society
- 1982 National Medal of Science, USA
- 1988 Honorary member, Japan Academy
- 1991 Member, American Philosophical Society
- 1991 Honorary Doctor of Science, Rutgers, the State University of New Jersey
- 2002 Honorary degree, École Normale Supérieure, Paris, France
- 2002 Honorary degree, Tokyo University, Japan
- 2007 Honorary degree, Tsinghua University, Beijing, China

ACKNOWLEDGEMENTS

The authors are very grateful to Susan Anderson for sharing photographs and reminiscences of her father. We would also like to thank Firestone Library at Princeton University for providing access to Phil’s archival notebooks. Many of Phil’s colleagues, students, postdocs and friends have contributed to this memoir, and we deeply appreciate your recollections and photos of dear Phil. Finally, we should like to thank the hospitality of the Aspen Center for Physics,

which is supported by National Science Foundation grant PHY-2210452, where the final stages of writing this memoir took place.

The frontispiece portrait photograph was provided to the Royal Society by the subject. Copyright unknown.

AUTHOR PROFILES



The three authors in Aspen, Colorado: (from left to right) Piers Coleman, Clare Yu and Premala Chandra, who were all graduate students working with Phil Anderson in the 1980s.

Premala Chandra

Premala ‘Premi’ Chandra is a materials-inspired theorist who is a professor in the Department of Physics and Astronomy at Rutgers University (USA). During her doctoral studies, Premi was welcomed as a visiting student in Phil’s condensed matter group; there she became interested in frustrated magnetism, a research area that continues to fascinate her to this day. Premi maintained contact, both scientifically and socially, with Phil from that time onward. Premi is a fellow of the Institute of Physics (2004) and of the American Physical Society (2013).

Piers Coleman

Piers Coleman is a theoretical physicist, educated at Cambridge and Princeton. Under Phil Anderson, he developed the slave-boson method in the 1980s—a powerful technique for modelling heavy-fermion materials and unconventional superconductivity. As a distinguished professor at Rutgers and the University of London (Royal Holloway), he has made landmark contributions across topics such as quantum criticality, topological Kondo insulators, predicting the gapless surface states of SmB_6 and frustrated magnetism. Coleman is director of the International Institute for Complex Adaptive Matter and the Hubbard Theory Consortium in London. He is the recipient of a Sloan fellowship (1988) and a fellow of the American Physical Society (2002). Coleman’s *Introduction to many-body physics* (Cambridge University Press, 2015) is a widely read text in the field.

Clare Yu

Clare Yu is a distinguished professor of physics and astronomy at the University of California, Irvine. A Princeton alumna (AB 1979, PhD 1984), she did both her senior thesis and PhD thesis with Phil Anderson. She credits Phil with teaching her how to think about physics. Her research in theoretical condensed matter physics includes disordered systems and microscopic noise mechanisms that limit coherence in Josephson junction qubits. Her research group also applies statistical physics and simulation techniques to biological questions, including intracellular transport mechanisms and the spatial distribution of immune cells within the tumour microenvironment. She is a fellow of the American Physical Society (2005), the American Academy of Arts and Sciences (2019) and the American Association for the Advancement of Science (2021).

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