The Anderson Effects*

T V Ramakrishnan

I outline in this article, the work of the theoretical physicist P W Anderson. He was perhaps the most influential figure in condensed matter physics in the second half of the 20th Century, the 'Gruff Guru'. His epochal contributions and impress on the field saw it emerge from obscurity as the largest subfield of contemporary physics.

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An era has ended with the passing away of P W Anderson, a theoretical physicist, at the age of 96, in Princeton, New Jersey, USA., on the 29th of March, 2020.

We generally associate a phenomenon in science with its discoverer; for example, the Raman Effect. I believe that P W Anderson, through his discoveries in physics, through the influential articulation of his attitude to physics, and through his impress on associates and on the field of condensed matter physics[1] in general, had a far-reaching impact. I describe below these Anderson Effects, which were nearly fifty years in the making. I also mention some of his characteristics as I saw them.

When Anderson started his career, in 1950 or so, solid-state physics (often known derisively as 'squalid state physics') was an obscure activity in Physics. The great physicist Niels Bohr had not heard of it. It was due to the sustained pathbreaking contributions of Anderson (among others, but perhaps more than those of any other) that the field has grown into perhaps the largest single activity in physics. This is not only because of the large number of applications and the variety of systems as well as phenomena in this area, but also because of completely unexpected effects unearthed, the intellectual depth of the contributions, and connections with the rest of physics and of science.

Keywords
Condensed matter physics, superconductivity, emergence, antiferromagnestism, disordered systems, RVB state, BCS theory.

[1] The name condensed matter physics gained currency from 1967 or so when Anderson and Heine suggested that the physical study of matter in which the parts are condensed together be called so; the main constituent was called solid-state physics earlier.

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Figure 1. P W Anderson at eighty three.

Another effect is this: In 1972, Anderson wrote a pathbreaking paper called 'More is Different'. It was a clarion call. It woke us up to the reality of emergence, at a stage when 'real' science was equated with reductionism, though emergence has always been a known reality in science. It reminded us that "At each stage (of complexity) entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as the previous one". "The main fallacy in this kind of (reductionist) thinking is that a reductionist hypothesis does not imply by any means a 'constructionist' one". "The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity". The last is a reference to the common belief that once the basic laws of nature are known, the rest is 'just' a relatively straightforward if painstaking, matter of putting things together according to them. (There is a reprint of this paper in this issue, with an introduction by R Nityananda). This work has already had a great positive effect on physics and on areas of science beyond. I guess that this second 'Anderson Effect' is important for the survival and growth of science.

The third Anderson Effect is through his associates, and through his effect on those who had even a chance encounter with him. About the first, as mentioned by G Baskaran, many physicists in this part of the world (including me) have had influential association with him. The consequences of this can be seen in their effect on the next generation of physicists. This is a common propagating and expanding effect. An example of the latter is Doug Osheroff's encounter with him, as described by Baskaran. Doug had found, in 1972, two glitches in the pressure vs. temperature curve of fluid He^3 at temperatures of order 2mK. (He was a PhD student in Cornell then). He and his mentors thought that the glitches were connected with the solidification of He^3; a paper by them describing the result this way was accepted for publication in the prestigious journal *Physical Review Letters*. Doug went to Bell Labs, where Anderson worked, for a job interview, and talked to him about his results. Anderson's eyes lit up, and he said that they were probably seeing superfluid He^3, a new and very much sought after phase of quantum matter, and made a number of related suggestions. Several months of difficult experiments later, this was confirmed.

Doug Osheroff and his mentors were awarded the Nobel Prize in 1996 for this discovery. This kind of thing, a sharp recognition that something major may be involved in an observation which might be missed or misinterpreted, and its persuasive communication, has happened far too often with Anderson to be a fluke.

I now elaborate on the first Anderson Effect by mentioning a few examples. Many of his contributions are now part of the basis of modern condensed matter physics, and also of its present active frontiers. Some have had consequences outside this field—in physics, in computer science, and in biology.

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In condensed matter physics (both its quantum or hard, and classical or soft parts) one is close to a variety of natural phenomena and to controlled experiment. One is thus close to the wellspring of modern science in the sense of Francis Bacon (1561–1620), one of its founding spirits. (He emphasized the importance of experiment over contemplation, and over scriptural authority. He also felt that science should aim at practical inventions for the improvement of all human life). Anderson's inspiration is Baconian, as he has said. He starts with experiment, makes a hypothesis and an appropriate theoretical model; interestingly, his inspiration in solving the model and in predicting its consequences is natural reality of whose interconnected nature he has profound knowledge, as pointed out by Baskaran. Because of his training and the milieu in which his work was done, his knowledge of formalism is broad and deep; it is deployed as necessary, but he is primarily a natural scientist.

Perhaps the first of Anderson's major contributions is his analysis of antiferromagnetism (1952). I describe this in some detail because it touches on many of the broad themes in his life work, e.g. broken symmetry, quantum phenomena in condensed matter, emergence, etc. For purposes of magnetism, atoms are modelled simply as magnetic moments or spins. Heisenberg showed that quantum mechanically, the difference in magnetic energy between possible magnetic states of atoms can be modelled by a coupling between their spins. If this coupling, which is strongest between nearest neighbour spins, is such that the energy of a pair is lowered when the spins are parallel, it is called ferromagnetic and leads to all the spins pointing parallel below a certain temperature. Crudely, this is the state of affairs in the metals Fe, Co, and Ni. In a ferromagnet, all the spins are parallel and the total spin points in one of infinite possible directions, in each of which the system has the same energy; such spin states are degenerate eigenstates of the Hamiltonian which determines their dynamics. Thus ferromagnetic order, by choosing one out of an infinite number of directions for the total spin, breaks a symmetry. However, there is another large family of magnetic materials, consisting of insulators. Members of this family have no net magnetization; magnetic ordering of a different kind seems involved. One can guess that the interaction between spins is anti-ferromagnetic in these and that is the cause of the difference. The lowest energy state ought then to be one in which the nearest neighbours form spin singlets because of the antiferromagnetic interaction, without net magnetization or spin. One would then think that the material ought to consist of some combination of such spin singlets.

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In sharp contrast to this, Neel proposed in 1932 that there exists a stable state for spins with pairwise antiferromagnetic interactions

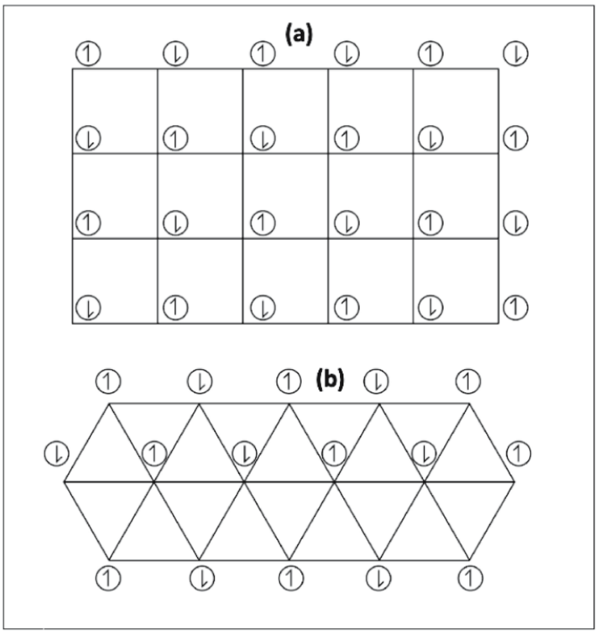

Figure 2. Two different lattices in two dimensions: **(a)** Square planar lattice, with magnetic moments shown by arrows on different sublattices, also square. **(b)** Triangular lattice.

in which they point one way on all sites of one atomic sublattice, and the opposite way in the other. The sublattices interpenetrate each other and have an equal number of spins. This arrangement is such that the nearest neighbours of each spin point opposite to that spin. (These nearest neighbours are all members of the 'other' sublattice). The material as a whole has no net magnetization though each sublattice has, and it has this kind of well-defined magnetic arrangement extending over very long distances; theoretically, infinite distances. This is called a long-range order. (As a concrete example, one can visualize a square lattice in the plane of this page, in two dimensions; the spins are all situated at the corners of the squares. The two sublattices are also square lattices, as one can see by drawing the figure). The ordering hypothesized by Neel was established experimentally in 1951, using the scattering of neutrons from the material. This is a new kind of broken symmetry found in Nature. The Neel state is *not* a collection of spin singlets; it is not an eigenstate of the Hamiltonian. How then can it be the ground state? Anderson confronted this mystery directly. He showed first that inevitable quantum fluctuations with respect to the Neel state are important in several ways. They reduce the sublattice magnetization by amounts which can be measured.

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Quantum mechanically, there are transitions between states in which the sublattice magnetization points in different directions so that at long enough time scales, these states get all mixed up; the net sublattice magnetization averages to zero. However, the time scale is long; it could be larger than the age of the universe! Anderson proposed and implemented an imaginative rotor model for what happens to the antiferromagnet as a *whole*, i.e. collectively. Crudely, the sublattice magnetization can be thought of the direction in which the collective rotor points. The rotor is described by the moment of inertia of the entire antiferromagnet and by a quantum mechanical term which changes the direction in which the rotor points. The lowest state of this rotor is one which mixes up all the directions; he showed that the time scale for achieving such a state is astronomical, as we have mentioned above. So, the emergence of the broken symmetry state seems the first step in understanding how the symmetry inherent in the quantum mechanical equations of motion is restored. Almost always, this step is not taken because symmetry restoration occurs at astronomically long time scales.

Scientifically, this early foray of Anderson into magnetism is profound; it deals explicitly with the unusual observed breaking of symmetry, its consequences and its restoration. (Because of its familiarity, our minds do not record the fact that a solid is a similar example of broken symmetry; the quantum mechanical laws of motion are invariant under continuous translation and rotation. The crystalline solid is unchanged only under specific translations and rotations). One has, first, the fact of broken symmetry, an *emergent* property. This broken symmetry state has novel characteristic properties, like appropriate kinds of rigidity (e.g. it hurts when you kick a stone), absent in the phase with unbroken symmetry. Quantum mechanics restores the symmetry, often on astronomical timescales. By now, the ideas first articulated by Anderson are part of the basis of the physicist's description of interacting particles and fields.

Some others among Anderson's contributions to magnetism stand out because of their foundational nature and enormous consequences. At about the same time as the above work on quantum effects in antiferromagnetism, his mind turned to the question of why antiferromagnetic exchange? It is an empirical fact that there are thousands of insulating magnetic materials, e.g. magnetic oxides which are antiferromagnetic and ferrimagnetic, etc., with hardly any ferromagnets among them! This would not even be possible if there were no basic antiferromagnetic interaction. What is its origin? Why is it endemic in insulators? In the thirties, Hendrik Kramers had argued that superexchange, involving quantum mechanical admixture of higher energy 'virtual' states with the ground state of the magnetic ion, is the cause. Anderson, in work which spanned almost the entire decade of the 1950s, gave this idea flesh and blood and unique intellectual depth. He identified materials, chemical families, crystal structures, systematics in properties, and connected each one of these with atomic-level quantum realities (e.g. orbitals). The practical importance of this cannot be gainsaid: for example, ferrites, a family of insulating ferrimagnets (with only basic antiferromagnetic interactions between the nearest neighbours) are the staple material in electronic inductors, transformers and electromagnets. Characteristically, Anderson realized that at the basis of superexchange (now known as the Kramers–Anderson or Anderson superexchange) was strong electron correlation. This is the fact that for the d orbitals involved there is a large energy difference between states with different d electron numbers at a given site arising from the strong Coulomb repulsion between like charges, so that the numbers and dynamics are strongly correlated. This absence of fluctuation in the number of d (or local) electrons is the origin of associated magnetic moments. This broad idea was at the same time being developed by Mott, who also realized that it could be the basis for electrons staying 'home' in a certain family of solids and thus of their being insulators (now known as Mott insulators; the phenomenon is often called the Mott phenomenon). These antiferromagnets are Mott insulators.

Anderson was intrigued by the fact that dilute concentrations of magnetic atoms, dissolved in some metals, show magnetism while the same atoms dissolved in some other metals do not show magnetism. This fundamental dichotomy in behaviour led him to develop in 1957 what is known as the Anderson model for a magnetic impurity in metals. In his model, there is an effective local repulsion between electrons in the same atomic orbital of the magnetic impurity, as mentioned earlier. This stabilizes its magnetic state which has a definite number of electrons on the atom. This would be all there is, for an isolated atom. But if this atom is embedded in a metal, quantum mechanically, the 'magnetic' electrons of the impurity mix (hybridize) with the electrons of the metal; the local number fluctuates with time. Anderson's model includes this explicitly. He showed in a self-consistent solution of this problem that the magnetic moment exists for relatively small hybridization, while it disappears for larger values. This Anderson model is the parent of quantum impurity models in solids and is a crucial ingredient of modern electronic structure calculations of solids which include effects of strong electron correlation.

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There are many magnetic systems in which the interactions are ferromagnetic between some pairs while antiferromagnetic between others, with a random distribution of these possibilities. These 'spin glasses' have quite unusual properties; the folklore was that as such a collection of spins is cooled, it freezes continuously into the most energetically favourable configuration decided by the nature of magnetic interactions of an atom with those in its vicinity. The model of Edwards and Anderson (1975) for such systems, and their novel analysis showing that there is actually a sharp transition into the spin glass state characterized by a precisely defined freezing criterion, galvanized and revolutionized the field. Further exploration showed that there are far-reaching parallels with many kinds of statistical systems which consist of a large number of interconnected parts. They could be interconnected neurons, a large number of cities (situated at different distances from each other) which a salesman is expected to visit, and the associated question of the optimization of travel time, etc. The directly inspired methods of combinatorial optimization have spawned and invigorated large areas outside physics.

Anderson returned to the question of the natural state of a collection of spins with antiferromagnetic interactions in the early seventies (1973). He considered antiferromagnetically coupled systems of spin (1/2) (in units of $\hbar$ or ($h/2\pi$)) which is the smallest value possible quantum mechanically and, therefore, with the largest quantum effects, and with lattices in which the two sublattice partitioning of Neel is not possible, e.g. a triangular lattice in two dimensions (unlike the square planar lattice mentioned above; a figure shows both the square planar and triangular lattices). He showed that for these, a superposition of spin singlets, known as the resonating valence bond (or RVB) state, is quite likely to be the ground state, compared to a version of the Neel state. This is a new avatar of a similar state conjectured for metallic electrons by Pauling. It is a quantum spin liquid, a very active field of modern condensed matter physics, chemistry, and materials research. Many candidate materials, which for these and other reasons do not order in the familiar Neel manner, have been identified and actively explored in the last few years. (The Neel state can be thought of as a spin solid). The RVB state is also the parent of high-temperature superconductivity, e.g. in the cuprates, in the approach of Anderson. This subject occupied him for more than three decades of his life, from 1987 onwards, and has been a rich source of other ideas as well. This is an area with which Baskaran has been associated from the very beginning of the field, and to which he has made many crucial contributions.

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A major contribution, which in a sense flowed out of the above, has to do with the ultimate fate of magnetic impurities in metals. Do they continue to be magnetic down to the lowest temperatures, even though they are coupled to the (spins of) electrons in the metal ? The journey began from a relatively obscure but longstanding phenomenon. It had been known for decades that the electrical resistivity of many metals with magnetic impurities shows a minimum as a function of temperature. This is unexpected because the resistivity of metals generally increases as thermal disorder increases. In a model with a pre-existing magnetic moment or spin coupled to the spin of conduction electrons of a metal, Kondo showed (1964) that to third order in this coupling, the scattering of conduction electrons (and hence the resistivity of the metal) increases as temperature decreases. This Kondo effect does account for the resistivity minimum. But it raises an uncomfortable question, which occupied physicists in the field for many years. The increase is logarithmically large as the temperature decreases, so it will cease to be a perturbative effect at lower temperatures. What happens then? Anderson was deeply concerned with this question . One of the lasting contributions which flowed out of his concern is the discovery that as the effect of the interaction of the local spin with higher energy electronic spin states is subsumed into its effective coupling with the remaining lower energy states, this effective coupling increases. As this process is carried to lower and lower electron energy scales, the coupling becomes stronger and stronger, and 'binds' the local spin and the conduction electron spin, a spin singlet results, and the magnetic moment disappears in the limit. This was the birth (1970) of a quantitative theory of the renormalization of coupling constants with the thinning out of degrees of freedom, a very pervasive and consequential idea in physics. (For example, the revolutionary work of K G Wilson in statistical mechanics which was featured in an earlier issue of *Resonance*[2]). A large family of metals with magnetic rare earth atoms called heavy fermions, are lattice systems of this kind. Farther afield, the interaction between a particular family of elementary particles is strong when their energies are low, but effectively weaker when they are high. This behaviour of strong interactions has a deep parallel with the Kondo effect.

There is an underlying fundamental phenomenon in degenerate Fermi systems (e.g. metals!) which was unearthed by Anderson in 1967; he realized that the state of a metal without a local potential and the state with a local potential are orthogonal in a singular way; one can think of the potential as exciting a large number of low energy particle hole excitations of the Fermi system with-

[2] Gautam Mandal, The Wilsonian Revolution in Statistical Mechanics and Quantum Field Theory, *Resonance*, Vol.22, No.1, pp 15–36, 2017.

out it. This catastrophically reduces the overlap between the two states. The orthogonality catastrophe has important consequences for many low energy/low temperature properties of metallic systems, including the above-mentioned disappearance of the local moment at low temperatures!

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Another direction which Anderson's creativity took was his contribution to our understanding of the electronic behaviour of disordered systems. In the 1950s, Feher had observed that the magnetic moments of phosphorus atoms, of which a dilute collection is doped into silicon, are localized (this may have been the first observation of a spin qubit, as remarked on much later by Anderson). Influenced by this, Anderson proposed, in 1957, a completely new major phenomenon, namely the localization of electrons moving in sufficiently disordered systems. The standard belief was that as disorder increases, electrons diffuse more and more slowly. Anderson argued in a paper titled, 'The absence of diffusion in certain random lattices' that this diffusion totally ceases beyond a certain disorder. Anderson was awarded the Nobel Prize in 1977 for this discovery. The strangeness of this effect is its existence; diffusion does not become slower and slower but totally ceases. This happens even when there is no potential well which confines the electron to a particular position; the disordered system has a random potential energy landscape. (Of course one can have a chance accumulation of appropriate random potentials which leads to a potential well. This was pointed out by Lifshitz; it is the cause of electron localization in a band of energies known as band tails). Mott argued that the insulating nature of a whole class of semiconductors, namely non-crystalline materials which may be solids (e.g. amorphous semiconductors) or even liquids (e.g. transformer oil!) has this electronic basis. It is a phenomenon common to waves in random media, e.g. light waves, sound waves, and even Rossby waves, which are ocean waves with wavelengths of order a hundred kilometres.

Anderson returned to this two decades later (1979). Electrical conductivity was shown to harbour measurable effects of impending electron localization; quantum interference between electrons travelling nearly oppositely in the random medium was identified as the cause. One of the consequences is that there is no truly metallic state in two dimensions. (I was a participant in this work).

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The third area of work in which the contributions of Anderson have a lasting impact is superconductivity, namely the peculiar phenomenon of the total absence of resistance to the flow of electrical current, as happens in many metals and alloys cooled to sufficiently low temperatures. Discovered in 1911 by Kamerlingh Onnes, with a long series of failed attempts at explanation, a successful microscopic theory was proposed in 1957, when Bardeen, Cooper, and Schrieffer argued that a superconductor results when electrons bind together to form (Cooper) pairs and these pairs form a coherent state, a condensate (the theory is generally known by the acronym BCS after its proposers). Anderson made a number of fundamental contributions here. For example, he showed that the theory when properly formulated so as to explicitly gauge invariant, namely such that physical properties do not depend on the choice of the phase of the electron field, namely of the gauge, several properties emerge. There are collective oscillations of the pair phase which are transformed to plasma oscillations (the natural collective modes of oscillation of (charge) density). The amplitude of the superconducting order parameter has oscillations with nonzero frequency, as noted by Higgs in a relativistic quantum field theory setting. These Higgs modes or Higgs bosons, observed first in 2012 in a momentous Large Hadron Collider (LHC) experiment, are considered to generate most of the mass in the universe, through their coupling with appropriate quantum fields. This is known as the Higgs or the Anderson–Higgs mechanism (1963). In work which seems far afield, Anderson, with Itoh, Ali Alpar, Shaham and others (starting in 1975) showed that the glitches observed in pulsars are due to the vortex creep in the neutron star superfluid!

Anderson was among the first to appreciate the importance of the phase of the superconducting order (parameter). The connected bizarre effects predicted by Josephson, e.g. the appearance of an ac voltage in a circuit consisting of two superconductors sandwiching a thin insulating layer, this circuit being maintained at a steady (dc) voltage, are by now the basis of a subfield of metrology, among other things. (Josephson, then a precocious PhD student who attended Anderson's lectures in Cambridge, was the first to clearly understand the significance of the phase of the superconducting order parameter; the first observation is due to Anderson and Rowell in 1963). Anderson strongly and clearly re-expressed recently the point that while the creators of quantum revolution in physics felt that the quantum domain is atomic, with classical physics being the description of the world at human scale, London, alone among the quantum pioneers, saw clearly that superconductivity and superfluidity are quantum effects on the macroscopic scale. This is especially timely because recent theoretical and experimental discoveries have revealed to us novel kinds of quantum matter characterized by nontrivial topological behaviour of atomic level electronic quantum states in them.

Then there is the sustained work on high-temperature superconductivity. Anderson proposed and developed with Baskaran and others a detailed RVB theory for high-temperature superconductivity, starting essentially immediately after its discovery in 1986–87. The broad point here can be stated this way. While so far we have no examples of superconductors which do not involve Cooper pairs of electrons, do the pairs form only if there is boson mediated attraction between them (as commonly believed) or can pairing happen in a system with only electron repulsion, and that too, strong repulsion? Anderson was the foremost to espouse the latter possibility, from the very beginning, clearly and strongly. This is very important because before this, under the influence of the phenomenally successful BCS theory, there was an implicit belief that there must be a bosonic excitation which mediates an effective attraction between electrons in order that Cooper pairs form. (Electrons repel each other so that this attraction is quite unusual; BCS argued that the relevant boson is the phonon or the quantized lattice vibration). By now, it is a commonplace belief that one can have pairing and superconductivity without neces-

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sarily a boson mediated attraction between electrons. The actual RVB theory may not be universally accepted; the reasons are sociological as well. However, to me, the opening up of the strong correlation (strong local electron repulsion) regime as a possible host for superconductivity seems a great contribution. Even more importantly, it has led to the intense exploration of this large region of electron physics.

In a book titled, *The Problems of Physics* (Oxford University Press, Oxford, 1987), A J Leggett identifies the four frontiers of physics as the large, the small, the complex, and the unclear. The first two are the conventionally obvious frontiers of growth of the subject, have a very natural grip on our imagination, and one believes that they are the 'real thing'. I quote from a truthful condensed matter physicist: "When I was an undergraduate, I thought solid state physics (a sub-genre of condensed matter physics) was perhaps the worst subject that any undergraduate could be forced to learn—boring and tedious, "squalid state" as it was commonly called. How much would I really learn about the universe by studying the properties of crystals?" The same physicist says, "But once I was introduced to the subject properly, I found that condensed matter was my favourite subject in all of physics—full of variety, excitement, and deep ideas. Many many physicists have come to this same conclusion". The work of Anderson, of which some aspects have been described above, and which is largely on the behaviour of electrons in condensed matter systems and on magnetism, helped establish the third frontier and introduced us to the richness of different parts of it. It provided the needed intellectual quality. It showed, as stated by Anderson in his paper 'More is different', and as quoted above, that "at each stage (of complexity) entirely new laws, concepts and generalizations are necessary, requiring inspiration and creativity to just as great a degree as the previous one". Anderson's work also helped establish strong natural connections between the different frontiers. We have mentioned some above. There are many more indications of their mixing. This seems to be necessary, inevitable and seems to be happening more and more.

Anderson's 1972 essay on emergence is especially timely in that modern science has come to be largely identified with reductionism. The re-emergence of emergence bodes well for the future of large areas of science and for their empowerment as well as self-belief. Starting from the 1970's, there has been a continuing and strong feeling that we are nearing the end of science. For example, the subtitle of a well-known book by John Horgan (Broadway Books, New York, 1996) titled, *End of Science* is 'Facing the limits of knowledge in the twilight of the scientific age'. This feeling is probably strongly influenced by the identification of science with reductionism. Anderson has been a vocal critic of this attitude. For example, in 1999, he wrote, "The reason that Horgan's pessimism is so wrong lies in the nature of science itself. Whenever a question receives an answer, science moves on and asks a new kind of question, of which there seems to be an endless supply." This is an expression of his belief (from within modern science) in emergence as the future of science; as the counterpoint to the belief in the end of science. However, there is also the view that the approaching end of science points towards what may be called 'rational mysticism'. As described by the Sanskritist and Indologist Frits Staal, "A rational mysticism is not a contradiction in terms; it is a mysticism whose limits are set by reason." Indeed, Horgan himself explored this possibility in a book of interviews called *Rational Mysticism: Dispatches from the Border Between Science and Spirituality* (Houghton Mifflin, New York, 2003). It seems to me that the questions implied by Anderson's essay on emergence lead us to metaphysical questions and to the fourth frontier of physics mentioned above, namely the unclear.

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>
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Anderson had a strong India connection. Baskaran has mentioned a few of the physicists from this part of the world who were his associates. It was in Bangalore, towards the end of 1986, that the first (impromptu) meeting on high-temperature superconductivity took place. A number of physicists had come for an international conference on valence fluctuations. Many of them were active in the field of superconductivity in the cuprates which had opened up just then; there was an enormous buzz about this discovery. A meeting was put together where some of the actors talked about the work going on in their laboratories, some others contributed their ideas. It was enlivened by vigorous exchanges. Anderson took part in all this. He returned to the US, and very soon there appeared in the journal Science, an article by him early in 1987, entitled 'The resonating valence bond state in La_2CuO_4 and superconductivity'. The very first explicit calculation of superconductivity in the cuprates is due to Anderson and Baskaran which followed a few months later.

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Anderson was driven to understand natural phenomena and experiments; to develop hypotheses encoded in mathematical models, and deduce consequences. These were checked against phenomena in turn; testable predictions were made. He was aware not of just the relevant experimental facts; he was also aware of the tangled network of connections between a large number of them. Some of these were obvious, some not. This heightened awareness gave him enormous self-belief; he was secure in that world. This also meant that he was quite idiosyncratic in what he valued in people and physics. He was quite independent-minded and was not excessively weighed down by the mathematical subtleties or difficulties of this theoretical approach or that. Because of his training and the milieu in which his work was done, his knowledge of formalism was broad and deep; it was deployed as necessary, but he was primarily a natural scientist.

An important factor in Anderson's stance as a scientist is his long association with the Bell Telephone Laboratories (known colloquially as Bell Labs), for 35 years from 1949 to 1984 (from the late 1960's, he had dual appointments, first at Cambridge and then at Princeton, where he subsequently was till the end of his life). While the Bell Labs is known widely for its role in the evolution of telecommunications, its uniquely liberal (and successful) interpretation of its raison d'etre meant that Bell Labs was the centre of perhaps the best and most interactive activity in condensed matter science for almost half a century. Work at Bell Labs has resulted in eight Nobel Prizes in Physics (including those for the discovery of the wave nature of matter, for the invention of the transistor, and for the discovery of the cosmic background radiation) and one in Chemistry. Two illustrative mottos of Bell Labs are, “get the best people in the world and get out of the way” and “theory should be on tap, not on top”. Decades of life in this high quality, broad range, contentious, unbelievably broad-ranged atmosphere helped make him.

Anderson was very democratic in spirit, a warmhearted holistic person. Perhaps it was related to his growing up on a farm in Urbana, IL (~the Midwest). He spent much of his childhood hiking, canoeing, and picnicking. He came from a family of “secure but impecunious academics”. For example, his father was a professor of plant pathology at the University of Illinois, Urbana. A friend and physics colleague told me how, as a person without academic ‘pedigree’, he had gone to a summer school where Anderson was a lecturer. Anderson befriended him, talked to him, listened to him, not patronisingly, but genuinely. Another friend had this to say. A young physicist excitedly told him, “You know, I talked with Phil (as PW Anderson was known to all) for almost an hour; he did not agree with anything I said”. Baskaran begins his article with his experience of a student walking into Anderson’s office and expressing himself.

The Andersons were very widely read and carried this lightly. A favourite genre of his was detective fiction: he was especially fond of Inspector Ghote, the Mumbai detective created by the writer HRF Keating.

When I began working with Phil in Princeton, around September 1978 or so, many conversations with him left me completely befuddled. This was hard on a rusty physicist low on self-confidence. After a few weeks of this, I felt I must ‘unburden’ myself to J M (Quin) Luttinger at Columbia, my PhD mentor. When I talked with him about it, he said, “Phil does not get things out beyond a certain point of clarity. But he is the most talented person in our field”. (Phil Anderson was a coauthor in a *Physics Today* obituary for Luttinger which specially noted the clarity of his published work and his lectures. I myself found that his classroom lectures had a deceptive simplicity). So, that was that. As months passed, I began to make some sense of his association of ideas and phenomena, and indeed became an interpreter to many other fellow travellers in the period 1978–81.

Anderson was also a first-degree master of the board game of strategy called Go (originally a Chinese game; now very strongly associated with Japan). Professor Brian Arthur, an economist and professor at the Santa Fe Institute, recalled one evening in the 1990s when a group of colleagues from the institute were discussing board games at a local restaurant, and he asked Professor Anderson if he played any. "Well, I play a bit of Go", he said. Professor Arthur recalled, "I pressed him". "Are you any good at it, Phil?" "Yes", he said. "How good?" "Well, there are four people in Japan who can beat me". Then a long silence. "But they meditate", he added.

Professor Anderson was the best, and perhaps the last (?) exemplar of a way of doing physics and thinking about it which is brought out in a sentence from the book containing selected papers by him (*A Career in Theoretical Physics*, World Scientific, Singapore, 2nd Edition, 2004)—"The contribution of Physics is the method of dealing correctly both with the substrate from which emergence takes place and with the emergent phenomenon itself....Ever newer insights into the nature of the world around us will continuously arise from this style of doing science".

> The contribution of Physics is the method of dealing correctly both with the substrate from which emergence takes place and with the emergent phenomenon itself.
>
> – P W Anderson

Anderson's technical contributions are spread over about 550 papers and several books. These are: *Concepts in Solids*; *Basic Notions of Condensed Matter Physics*; *A Career in Theoretical Physics*; *Theory of Superconductivity in the High Tc Cuprates*; *More and Different: Notes from a Thoughtful Curmudgeon*, etc. Of these, I believe that the last is the most accessible.

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Suggested Reading

P W Anderson, *More and Different: Notes from a Thoughtful Curmudgeon*, World Scientific, New York and Singapore, 2011. It is a unique kind of scientific autobiography. It also has a collection of some of his book reviews and occasional writings.