P. W. Anderson (1923–2020)

P. W. Anderson, an epochal figure in Physics, passed away on 29 March 2020, at the age of 96, at Princeton, NJ, USA. He was awarded the Nobel Prize in Physics in 1977 (which he shared with N. F. Mott and J. H. van Vleck 'for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems'). Anderson was named the most creative living physicist in a statistical survey in 2006. His foundational contributions, perhaps more than those of anyone else, transformed the field of condensed matter physics from obscurity to prominence. Even the name 'Condensed matter physics' is due to him[1].

Anderson was born in Indianapolis, Indiana, USA, on 13 December 1923. He grew up on a farm in Urbana, Illinois. His father was a professor of plant pathology in the University of Illinois, Urbana. As he says in his Nobel acceptance lecture, he came from a 'family of secure but impecunious mid-western academics' on both sides. His 'happiest hours as a child and adolescent were spent hiking, canoeing, vacationing, picnicking, and singing round the campfire' with a group of warm, settled friends of his parents. He was both an undergraduate and a graduate at Harvard, where he worked for his Ph D with J. H. van Vleck (later a co-winner of the Nobel Prize in 1977). He got a position in Bell Telephone Laboratories (Bell Labs) in 1949, where he would be for the next 35 years, till 1984. Bell Labs, formally the R&D laboratories of a telephone company, had a constellation of world class theorists and was a place where Anderson '…learned most of all, the Bell mode of close experiment – theory teamwork'.

He spent the year 1953 in Japan as the first Fulbright scholar there, and acquired a lifelong admiration for Japanese culture, arts and architecture, besides learning the board game GO (which he played throughout his life and of which he became a first Dan master). Starting 1967, he divided his time with other academic institutions, first with Cambridge (till 1975) and then with Princeton, where he became the full time Joseph Henry Professor of Physics in 1984, retiring to emeritus status in 1996.

The general stance of people who are conceptually oriented is reflected in this reminiscence of one of us (K.A.M.): 'Black holes, Supernovae, Big Bang or Higgs Boson catch our imagination more easily than magnetism, superconductivity, localization or spin glass. Part of the reason is our fascination with 'heavenly' objects; it is indeed difficult to be excited about the detailed properties of solids around us. Solid state, or condensed matter physics, is often seen as important for technology, while particle physics, astrophysics, etc. are considered to be about fundamental laws of the universe. That is exactly the perception I had, aspiring to study high energy theory, when I started as a graduate student at Princeton in the Fall of 1977.

'I had some vague idea about solid state physics during my undergraduate years at Dhaka University, Bangladesh, primarily because my would-be-wife was studying X-ray crystallography at the same time, as part of her Master's thesis. It did not appeal to me; I was looking at the stars. But as I became more aware of Anderson's contributions, it started to dawn on me that the beauty of nature's fundamental laws is not just hidden up in the heavens, although it is perhaps a more obvious place to look. The conceptual revolutions associated with Anderson's wide range of ideas on localization of waves, broken symmetry, non-ergodicity, to name but a few, are all equally fundamental, although clearly more difficult to appreciate. Indeed, it took the scientific community decades to appreciate the importance of his paper written (in 1957) on the absence of diffusion in certain random lattices, for which he received the Nobel Prize twenty years later.'

While looking at Anderson's contributions to physics, the very first fact that draws one's attention is this: They are all motivated by an experimental fact, and a desire to understand it in a fundamental way. The process of understanding leads to new models, fundamental principles and often, paradigms. To illustrate this, we mention his work in three areas, viz. disordered systems, magnetism, and superconductivity. The ideas of emergence and broken symmetry that led to paradigmatic shifts in our understanding of basic physics resulted from Anderson's pioneering work in these areas and we will mention them briefly towards the end of this article.

Disordered systems: In 1957, inspired by the experiments of his colleague Feher that magnetic moments ('spins') of a dilute collection of phosphorus atoms in silicon do not seem to change their direction although they interact among themselves (absence of spin diffusion), Anderson proposed a new and simple model for 'spinless' electrons in a disordered solid. He used this model to study electron diffusion and showed that beyond a critical disorder, electron diffusion stops entirely; it is not that it becomes very slow. This general phenomenon discovered by him is known today as Anderson localization.

As mentioned above, Anderson was awarded the Nobel Prize in 1977 for this discovery a full twenty years after the paper was published. The physics community did not pay much attention to this discovery; nor did most believe in it. Mott, almost alone among physicists, saw that the theory of Anderson localization provided the conceptual underpinning for the existence of an entire class of materials, namely solid but amorphous semiconductors (not to mention transformer oil!) and that a number of applications could be developed. These insulators were called *Anderson Insulators* by Mott. The interference which causes Anderson localization is common to a variety of wave phenomena in nature, including Rossby waves (ocean waves with wavelengths of order of 100s of kilometers). In 1979, more than two decades after the original work, Anderson and three of his collaborators (including one of the authors, T.V.R.) realized in their scaling theory of localization, that the consequences of localization can be accessed experimentally by a property that can be measured quite easily, viz. the electrical conductivity. Scaling theory of localization is still a very active area of research with potential consequences for nano-electronics and quantum computation.

Magnetism: Anderson was concerned in the 1950s with the question, 'what is the origin of *anti*ferromagnetic interactions between spins?' (In the early years of quantum mechanics, Heisenberg had shown that a consequence of the identity of electrons is an effective *ferro*magnetic interaction between a pair of electron spins. This was called 'exchange' interaction). Anderson's work provided a general framework and unique intellectual depth to the idea of 'super exchange' as a mechanism (proposed in an embryonic form by Kramers in the 1930s). He identified classes of relevant materials. He also identified strong correlations of electron motion caused by electron repulsion, as the origin of insulating behaviour in substances that are nominally expected to be metals. Such insulators are now known as Mott insulators and the phenomenon is often called the Mott phenomenon, as Mott also developed these ideas independently. Insulating antiferromagnets (and ferrimagnets) are Mott insulators. Interestingly, Anderson shared the Nobel prize in 1977 with Mott.

Certain magnetic atoms lose their magnetism when dissolved in non-magnetic metals. To explain this quantum phenomenon, Anderson proposed, in 1961 a model (commonly known as the Anderson model for local moments). This work was also cited in the Nobel Prize awarded to him in 1977. One of Anderson's lasting contributions to this field is his study of what happens to the system as the temperature tends to zero; this led to his formulation (1970) of a quantitative theory of the renormalization of coupling constants with the thinning out of degrees of freedom – a very important idea in physics. His discovery that coupling constants grow at low energy scales foresaw the (Nobel Prize winning) idea in elementary particle physics – that of 'asymptotic freedom' (1973) in the strong interaction between quarks.

Returning to antiferromagnetism, quantum mechanics tells us that an antiferromagnetic interaction between spins leads to a ground state in which the pair has zero total spin, i.e. a spin singlet state. However, the Neel antiferromagnetic ground state observed in solids is not a superposition of spin singlets, although the total spin is zero. One of Anderson's most important contributions (1952) is the realization that this emergent state spontaneously breaks the symmetry of the quantum equations of motion. In this paper, Anderson developed a model in which the entire antiferromagnet is treated as a single quantum rotor, and demonstrated that symmetry is restored, but on astronomical time scales. Hence, the emergence of broken symmetry is a reality. Anderson says of this paper, whose innocuous sounding title is 'An approximate quantum theory of the antiferromagnetic ground state', that 'it contains the seeds of all my further ideas on broken symmetries, Goldstone modes, and the relation between microscopic and macroscopic physics'.

Anderson returned to this problem in the early seventies (1973). He showed that for some families of systems, a superposition of spin singlets (a resonating valence bond or RVB state, first proposed by Pauling for graphite, etc.) is quite likely to be the ground state. The study of Quantum Spin Liquids (as these states are known today) has become a vibrant field. In 1987, Anderson proposed that the parent state of high temperature superconductivity (e.g. in the cuprate superconductors) is an RVB state. A metallic RVB state, relevant for normal state of cuprates occupied his attention for the last three decades.

There are many spin systems where the effects of disorder and magnetism are inextricably mixed. In such systems competing interactions determine the dynamics of the spins and the spins cannot decide in which direction to point. This is termed 'frustration'. In 1975, Edwards and Anderson proposed a model for these systems. Their novel analysis opened an entirely new direction, going far beyond condensed matter physics. There are many systems in nature that can only be explained by competing influences between the system's components. Consequently, the Edwards–Anderson model has far reaching implications for a wide range of phenomena such as neural networks, combinatorial optimization, stock markets, etc.

Superconductivity: The Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity burst upon the physics scene in 1957, almost five decades after superconductivity was discovered in 1911. There was, within the community, acceptance, relief and equally, skepticism. Anderson clarified many of the basic issues and this opened fertile directions of research with far reaching implications. We shall mention two here. In his study of BCS superconductivity, Anderson showed that the massless Goldstone mode in a superconductor turns into a massive plasmon. As it turns out, this is the same phenomenon by which all elementary particles in the universe acquire mass, viz. the Anderson–Higgs mechanism of mass generation in elementary particles (Higgs and Englert won the Nobel Prize for this in 2013).

The second major contribution of Anderson was to plant the seed for the eventual discovery of the Josephson Effect. Brian Josephson, then a student who took Anderson's course in Cambridge, is supposed to have taken Anderson's casual comments (about tunnelling current and its relationship to the phase of the superconducting order) seriously, and worked out the details. Anderson encouraged Josephson to publish the latter's calculations, which became the Nobel Prize winning Josephson Effect. Most interestingly Anderson, in collaboration with Rowell, was the first to demonstrate experimentally the existence of the Josephson Effect in a superconductor, putting to rest the skepticism of the community about this phenomenon.

Several years later, Anderson[2] re-emphasized that while the creators of the quantum revolution in physics felt that the quantum domain is atomic (with classical physics being the right description of the world at macroscopic scales readily accessible to humans), London alone among the quantum pioneers, saw clearly that superconductivity and superfluidity are quantum effects on a macroscopic scale. This is a very timely reappraisal because recent theoretical and experimental discoveries have revealed to us, novel kinds of quantum matter. Their strange (and potentially revolutionary) macroscopic properties at room temperatures are related to non-trivial topological properties of electronic quantum states at the level of atoms. This was one of Anderson's abiding concerns: macroscopic quantum phenomena in condensed matter physics.

Turning to disordered superconductors, a theorem proposed by Anderson in the context of BCS superconductivity, posits the equivalence between time-reversed electron pairs and the original Cooper pairs of electrons with opposite momenta and spin. This turns out to be crucial in understanding the interplay between disorder and superconductivity. The motivating experimental fact is that superconductivity seems insensitive to addition of nonmagnetic impurities, but is adversely and strongly affected by even a small amount of magnetic impurities. (The former does not break time reversal invariance, while the latter does.)

In 1975, Anderson and collaborators (Itoh, Alpar, Pines and Shaham) published an influential paper on the rheology of neutron stars. They[3] proposed an explanation for the observed glitches in pulsar periods. According to Anderson and collaborators, vortex creep and collective motions of vortex bundles in the rotating superfluid crust of neutron stars lead to star quakes and observed gtitches in pulsar periods.

It was early November 1986. One morning Anderson walked into the office of one of us (G.B.) and placed a photocopy of an article and said, 'we should work on this'. It was the paper by Bednorz and Müller on their discovery of high T_c superconductivity in Ba-doped La_2CuO_4. G.B. also got excited and developed a theory which did not convince Anderson who felt that Mott insulating nature of undoped La_2CuO_4 plays a key role. According to Anderson, the RVB theory for high T_c superconductivity in doped Mott insulating cuprates crystallized in his mind during his trip to Bangalore in December 1986; in this, a magnetic measurement of P. Ganguly and C. N. R. Rao (Indian Institute of Science, Bangalore) on La_2CuO_4 was valuable. His celebrated preprint on the RVB theory of superconductivity appeared very soon. By the first week of January 1987, G.B. was convinced of the correctness of Anderson's approach and became a partner in the long journey of RVB theory. There were agreements, disagreements, and happiness in the most enjoyable journey.

The broad issue here can be stated as follows. Can pairing also 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, and did so unequivocally in the RVB theory he proposed. This is very important because prior to Anderson's suggestion, there was an implicit belief (which had much to do with the phenomenal success of the BCS theory) that for Cooper pairs to form, there must be a bosonic excitation which mediates an effective attraction between electrons. (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.) While the actual RVB theory may not be universally accepted, Anderson's great contribution was to advocate the strong correlation regime as a possible host for superconductivity. Even more importantly, Anderson's suggestion led to an intense exploration (still going strong!) of the area of 'strongly correlated electronic systems'.

Emergence and broken symmetry: Anderson's increasing awareness of the subject matter of science resulted in his path-breaking paper, 'More is different'[4]. It is fair to say that, as condensed matter physics has grown over the decades, this rallying cry has changed the character of the field and given it immense self-belief. It woke all of us up to the reality of emergence, at a stage when 'real' science was equated with reductionism, although emergence has always been a known reality in science. It reminded us that at '…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 … (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 bit 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 these.

A concept immeasurably deepened by Anderson is that of broken symmetry, which he emphasizes as an example of emergence. In matter, states are realized that break the symmetry of the laws of motion which govern the behaviour of the constituents of that piece of matter. For example, the laws of motion of atoms that constitute a crystal do not change if the origin of the coordinate system used to define their location changes continuously, or if the coordinate system is rotated continuously by any amount. But a crystal breaks just this symmetry; it is invariant only under certain discrete lattice translations and rotations. Among other things, Anderson showed that characteristic rigidities follow when symmetry is broken (e.g. it hurts when you kick a stone).

In some cases, the symmetry is restored by quantum mechanics but this happens typically at astronomical time scales. Broken symmetry is itself emergent. For instance, it does not make any sense to think of an atom as a solid or a liquid; but a collection of atoms can have such a property. Similarly, we cannot think of an atom of lead as a superconductor. But when a collection of them is cooled below a certain temperature, the piece of lead becomes a superconductor – an emergent broken symmetry state. This is not merely a vacuous verbalization as there are a large number of measurable consequences that he realized and explicated (e.g. in his book, see ref. 5.).

An important aspect of Anderson's way of doing physics was the engagement he had with experiments –both data and detail. He was not merely aware of the relevant experimental facts, but understood the tangled network of connections between several of them. Some of these were obvious, others not. One of us (V.N.M.) notes that Anderson '…would pour over data diligently. I have seen him magnify an experimental curve (using the photocopy machine), trace the curve on wax paper and replot it on graph paper – trying to read an exponent here, a bump there…Often he would narrow down on some feature in the data that many would completely overlook. It was almost as though he were coaxing the entire answer from the very data itself.' This heightened awareness gave him a unique security in the world his mind inhabited. This also meant that he was quite idiosyncratic in what he valued in people and in physics. He was quite independent minded, often contrarian (his last book is called *More and Different: Notes from a Thoughtful Curmudgeon* (World Scientific, Singapore, 2011)) and was not excessively weighed down by the mathematical subtleties or difficulties of this theoretical approach or that. He was, for much more than a generation, the 'gruff guru' of the field, as described in an interview[6].

Anderson's stance in science is captured by the following paragraph from his Nobel lecture: '…One of my strongest stylistic prejudices in science is that many of the facts Nature confronts us with are so implausible given the simplicities of non-relativistic quantum mechanics and statistical mechanics, that the mere demonstration of a reasonable mechanism leaves no doubt of the correct explanation. This is so especially if it also correctly predicts unexpected facts… Very often such a simplified model throws more light on the real workings of Nature than any number of "ab initio" calculations of individual situations, which even where correct often contain so much detail as to conceal rather than reveal reality. It can be a disadvantage rather than an advantage to be able to compute or to measure too accurately, since often what one measures or computes is irrelevant in terms of mechanism. After all, the perfect computation simply reproduces Nature, does not explain her…'. Indeed, Anderson's emphasis was always on the explanation of a physical phenomenon rather than detailed calculations not moored in empirical fact. While this may be called a 'stylistic prejudice', it is perhaps more apt to say that this approach acquired an almost ethical dimension in Anderson's view of scientific research.

Anderson was very democratic in spirit – a happy, warm-hearted and liberal-minded person. Perhaps it was related to his formative years. A friend and physics colleague recalled how, as a person without academic 'pedigree', he had gone to a summer school where Anderson was a lecturer. Anderson befriended him, talked with him, listened to him, not patronizingly, but genuinely. One of us (V.N.M.) remembers the following incident about how he and his collaborators disagreed with one of Anderson's ideas: 'Bernhard Edegger (a collaborator, who was then a graduate student at Frankfurt) planned to visit Princeton and told me, "I am going to show Phil how he is wrong. It seems you don't know how to do this." So, on his first day in Princeton, I took him to Phil's office and introduced him to Phil saying, "Bernhard is here to show you where and how you are wrong" and returned to my office. After a couple of hours, I found a tired and dispirited Bernhard at my door. I asked him, "What happened?" Bernhard gave me a tearful look and said, "Phil still thinks he is right". I told Bernhard that he must have done a good job because it is not often that Phil spends a couple of hours discussing with someone – especially someone telling Phil that he was wrong! Later, I found out Phil liked Bernhard quite a bit; he even told me once, "Bernhard is an uncut diamond"…'.

Friends of Anderson recall that he could be impetuous at times in a very funny way. One of us (V.N.M.) recalls his first meeting with Anderson: '…Phil took me along to the cafeteria at the Institute for Advanced Study in Princeton (one of his favourite luncheon places) for lunch. I parked my car and we were making our way to the cafeteria when Phil turned suddenly and walked up to a pick-up truck parked nearby. Showing great purpose and determination, he tore a bumper sticker off the truck (it was one of those "Guns don't kill people; People kill people" NRA stickers). I was transfixed and had an appalling vision of a truck driver with rippling muscles, charging at Phil.…' (Luckily, this did not happen!).

In a book containing his selected papers[7], Anderson remarks that '…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…' Phil Anderson was the best, and arguably the last exemplar of this way of doing Physics.

1. Anderson and Volker Heine renamed their group in Cambridge, originally called 'solid state theory', as 'theory of condensed matter' in 1967. This is the current name for the field, which is concerned with the 'condensed' phases that appear whenever the number of constituents in a system is extremely large and the interactions between the constituents are strong.
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