In memory of Philip W. Anderson

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Philip Warren Anderson is one of the founding fathers of modern condensed matter physics. With his death on Sunday March 29, we have lost one of the most influential physicists of the 20th century.

Philip Anderson was born in 1928 in Indianapolis, Indiana. He obtained his PhD degree at Harvard University with John van Vleck. He spent most of his career at Bell Labs, New Jersey. In 1977, he shared the Nobel Prize in Physics with his thesis supervisor van Vleck and his colleague Nevil Mott. In 1984, he became the Joseph Henry Professor of Phyiscs, emeritus, at Princeton University, and was still very active in physics. One of his doctoral students, Duncan Haldane, also later became a Nobel laureate. Outside physics, Anderson was a keen hiker and gardener, and seemed to be knowledgeable about many things. When he once visited us in the Netherlands we found out that he even seemed to know the names of many bird species.

Anderson made many original contributions to theoretical physics, guided by his unique intuitive way to grasp the physics long before it is captured by mathematically exact formulas and observed in experiment. His intuitive approach was apparent from his presentations, where fresh ideas were often still in progress, partly worked out but not always convincing for the audience. The spontaneous breaking of gauge symmetry in superconductors, for instance, was predicted by Philip Anderson in 1963 [1] before the phenomenon was discovered in the field of particles physics by Englert, Higgs and Brout in 1964 [2]. His prediction in 1958 that extended electron states can become localized due to the presence of disorder - which led to the Nobel prize in physics in 1977 - came out of nowhere.

It was maybe for that reason that the now famous paper "Absence of diffusion in certain random lattices"[3] was hardly noticed by colleagues in the years immediately after it was published. The field of localization due to disorder gained tremendous momentum with the advent of the scaling theory of localization [4], that was published in 1979 by Anderson, together with Ramakrisnan, Abrahams and Licciardello, together better known as as the *gang of four*. The scaling theory provided universal and simple arguments on how and when electrons localize. These arguments were so universal, so accessible, and so convincing, that no reason existed why they should not apply to all types of waves, including light and sound. In his "Theory of white paint", published in 1985[5], Anderson speculated that his ideas on localization of electrons could apply to electromagnetic waves propagating in disordered materials, although with the perturbing role of light absorption subtly different from the dephasing of scattering conduction electrons.

FIG. 1. A painting referred to as Anderson's Garden, hanging in Anderson's office. The colleague who offered it is not known to us, and was taken from Ref. [15].

While Anderson himself never really went deeper into the topic of light waves or optical materials, his work on random systems gave the inspiration to the birth of a new field called 'random photonics', where optical properties of disordered structures are explored. Transport and diffusion of light was of course already studied since a long time - for instance in the context of astrophysics - but interference effects were never taken into account.

The work of Philip Anderson on interfering conduction electrons in doped metals inspired many scientists working with classical waves to explore the concepts of localization brought about by interference of light and sound in disordered materials [6]. The initial holy grail was to observe the equivalent of Anderson localization for light waves, and to see if one could trap light inside a disordered photonic material. This quest gave rise to an explosion of theoretical and experimental activity that lasted for decades. Today the community still argues about whether or not it is possible to localize light in three dimensions [7]. This ongoing debate shows once more how profound the ideas of Anderson have been and how difficult it is to grasp them in theory and experiment. Thanks to this activity boost, the field of random photonics grew out to cover many topics, including mesoscopic transport, speckle correlations, and random lasing, and produced applications ranging from imaging to cryptography and spectroscopy. Today the exploration of localization in new media is still alive with recent studies being performed on cold atom gases. These investigations open up a wealth of possibilities to explore transport phenomena due to the combined, and experimentally controllable, effects of disorder and particle-particle interaction [8].

Whereas a theoretical physicist usually performs theory and simulation to understand an observation, Anderson's style is rather characterized as vision inspired by observation: He worked out his ideas in theory, but was never distracted by mathematical obstacles, keeping only the very essence, and was always strongly motivated by his vision of the end result. Numerical work he even called "undignified" in his Nobel lecture[9]. Today everybody knows that numerical simulation allows to verify the presence of the Anderson phase transition, and its full finite-size scaling, for a tight-binding Hamiltonian in just one second on a PC [10], but would anyone have discovered Anderson localization that way?

His visionary approach allowed Philip Anderson to contribute to many different fields. In 1975, Philip Anderson published, with Sam Edwards, the first theory revealing the nature of spin glasses [11]. The observed cusp of the magnetic susceptibility was explained with a simple Hamiltonian of spin interactions with alternating sign. With John Bardeen, Anderson became one of the world specialists on superconductivity, and the famous theorem on the stability of superconductivity against non-magnetic disorder bears his name. In his book on high-T_c superconductivity, published in 1997 [12] he rejects the celebrated Fermi liquid theory as the elementary theory for interacting electrons. This viewpoint was criticized by many peers in the field, and would have disappeared in the nearest wastebasket if it would not have been Philip Anderson who proposed it. He belongs to the very short list of post-Einstein theoretical physicists who really turned the world of physics upside down.

Philip Anderson never hid his opinion about important matters, including science policy and the philosophy of science. In 1987 [13], during a national debate about funding large scale experiments in the USA, he summarized his opinion - in a testimony to the House Committee on Science, Space and Technology - in the form of four slogans:

1. Science *can* be fundamental without being irrelevant.
2. Money is important, but manpower and education are more so, and money affects these.
3. The term "spinoff" should be erased from the language.
4. The golden eggs are very seldom produced by the golden geese.

This opinion paper makes the case for allocating financial and especially human resources also to small scale, curiosity driven research. Anderson defends his view that interesting fundamental science exists and can be investigated on human length scales and at energies at room temperature. The superconducting super-collider was cancelled in 1993, but Anderson's 4 slogans are still relevant today in any discussion on national and international funding. Since 1987, many "unforeseen" and "relevant" golden eggs have been laid down in the "small" blue skies of condensed matter physics and photonics.

In his brilliant and famous philosophical essay *More is Different* [14], Philip Anderson made a major contribution to the philosophy of science. By using the aforementioned spontaneous breaking of gauge symmetry as an example, Anderson positioned himself against *the theory of everything* and argued that new rules will always emerge as the complexity increases. His essay initiated a lively debate about the role of reductionism in science, by so many believed to be the ultimate method of natural sciences. Anderson emphasized its disadvantages and argued that advances in research will be hampered by the reductionist's tendency to over-simplify: while individual atoms behave in a precisely known way, their collective behaviour in a material can be totally unexpected and give rise to new, inspiring, phenomena.

Philip Anderson might recently have left us physically, but his work, his personality, and his vision on science will continue to inspire scientists all over the world for decades to come.

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