The fundamental parts of life

'More is different' is the title of an article by P.W. Anderson, published in Science in 1972. Anderson is an outstanding physicist and a Nobel prize winner (1979). The Science article is a somewhat unusual mix of profound scientific analysis and subjective appraisal of certain scientific disciplines. In the latter category falls his qualification of 'the arrogance of the particle physicist'.

Anderson's article is scientifically excellent and inspiring. He wrote it at the time when 'spontaneous symmetry breaking', also called 'the Higgs mechanism', was at the focus of attention in high energy physics. Prior to Higgs and to Brout and Englert, Anderson had discovered this mechanism in non-relativistic quantum mechanics. The relativistic version of Higgs and Brout and Englert got all the attention, perhaps that is why Anderson is not particularly fond of high energy physicists. The Higgs boson, by the way, is yet to be found...

Back to Anderson's article 'More is different'. He argues that finding the laws that govern the fundamental interactions in nature is not sufficient for understanding nature. 'Reductionism' leads us to these fundamental laws, but that does not make the opposite path ('constructionism') trivial, or easy, or even obvious. He is right of course.

He starts the argument by discussing the electric dipole moment. A fundamental particle cannot have an electric dipole moment. An electric dipole moment arises when charge is distributed over space. A fundamental particle is pointlike, that does not allow a charge distribution so no electric dipole moment can arise. There is a deeper, and more robust argument against fundamental electric dipole moments. The theory of the interactions of charged particles through electric (and magnetic) fields exhibits a profound symmetry: it does not distinguish right from left. An electric dipole would do exactly that and therefore cannot exist at the fundamental level.

Let us have a look at the ammonia molecule (as Anderson does in his article). Its chemical formula is NH_3, it has a three dimensional structure (a tetraeder) and definitely a dipole moment. The tetraeder, however, oscillates at a high rate between its two mirror imaged (with respect to the triangle formed by the three hydrogen atoms) states and thereby the average dipole moment becomes zero. So on average the dipole moment is zero.

There are, however, also molecules which are not symmetric with respect to their mirror image and do not oscillate from one state to the other: the symmetry is broken. Sugar molecules, for example, have a spiral structure like winding stairs. They can be either 'right-handed' R (like a standard corkscrew) or 'left-handed' L (the mirror image of a standard corkscrew). It is a property of the electromagnetic interaction, the force that holds these molecules together, that the L and R molecules have exactly the same (binding) energy: they are exactly equally stable. Both the L and R forms can be synthesized in the laboratory and they appear in equal quantities when this is done. Here is the very remarkable fact: in living organisms only one 'chirality', only one sense of rotation is produced. The same holds for proteins and for DNA. This is indeed very remarkable and as far as I know, unexplained. 'Life', the most complex of all complex systems, breaks the LR symmetry that is inherent in the fundamental laws that govern it.

The more complex a system is, the more information it can encode. ‘Reading’ what is encoded is the challenge for the scientists dealing with the analysis of the emerging phenomena.

For P.W. Anderson ‘broken’ symmetries indicate a hierarchical structure of science. It is easy to agree with him that this hierarchy by no means implies an intellectual hierarchy, or a hierarchy of science that is to be valued more, or less. The knowledge of the fundamental laws alone is not sufficient to predict all natural phenomena. Superconductivity is one famous example to illustrate this. The fundamental theory, in particular quantum mechanics, had been known for 30 years until finally the phenomenon was understood. (The experimental discovery of superconductivity precedes the theoretical explanation by almost two decades more: Kamerlingh Onnes discovered superconductivity in 1911).

What Anderson really was heading for in his article was a discussion of the complexity of living systems. He did not reach a conclusion, in the sense that he did not claim to have understood the transition from, the symmetry breaking between, inanimate and animate systems. But he asserted: ‘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.’

The article ‘More is different’ was written in 1972, almost 40 years ago. It reads very well and is fully relevant today. What progress has been made over the past 40 years? Too much to summarize here, but let me very briefly look at particle physics, i.e. let me look at the ‘fundamental end’. The charm quark was discovered. The tau lepton. The gluon. The W and Z bosons. The bottom quark, the top quark, the tau neutrino. Quantum-chromodynamics, the theory of quarks and gluons. The Standard Model of strong and electroweak interactions of quarks and leptons. However, an experimental confirmation of the Higgs field that breaks the symmetry from an ideal massless world to one where particles carry mass, a very early step up the complexity ladder very soon after the Big Bang, is still missing... The Large Hadron Collider, the powerful (and unique) particle accelerator of CERN is going to give us a clue soon.

The Higgs particle itself gives rise to speculations about a more comprehensive (but broken!) symmetry: supersymmetry, doubling the number of elementary particles and leading to more than one Higgs boson. There are other ‘evidence based’ speculations about dark matter and dark energy that indicate that there still is a lot to learn at the fundamental level...

So, 40 years after P.W. Anderson’s observation ‘More is different’ one can observe that ‘less’ has not been reduced to its minimal number of ingredients yet. There is still a lot of work to be done, a lot to be discovered at the fundamental end.

How about the other end, how about ‘more’? A lot of progress has been made there too. Our knowledge has grown enormously, the life sciences dominate the research agendas. ‘Genomics’ and its many ramifications are enormously important, scientifically and also economically. But I wonder whether new conceptual structures for new levels of organization, going up in complexity – from DNA to ‘us’ - have already been found. We need to continue looking and we will make progress, but great paradigm shifts and scientific methods that would fundamentally differ for these various levels of organization, I do not see them yet. Fundamentally, it is all science.

Jos Engelen
27-11-2011