Emergence

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Over the last couple of years, **emergence** has become a new buzzword in theoretical physics, the perspective of which I will be taking in the following. In that context, it normally refers to the appearance of (unexpected) features on a (bigger) scale that were not present on another (smaller) scale, which is thought to be causing the phenomenon at hand, i.e. the physics on one (microscopic) level gives rise to new, (effective) physics on a bigger scale. To a large extent, the notion of emergence is not at all new to physics. That phenomena on one level bring about very different looking phenomena on another level is precisely what has driven scientific curiosity over the last four hundred years. However, for most of that time, insight progressed from the large scale phenomenon to the small scale phenomenon. For example, the observation of the spectrum of visible light eventually led to Maxwell's equations of electrodynamics. The history of physics is that of **reductionism**, the antidote of emergence. It culminates in the call for a **theory of everything** or **grand unified theory** that captures all four fundamental forces in a single underlying interaction, that manifests itself in four different ways.

However, it is also widely accepted that a grand unified theory, even when it encapsulates all physical interaction, is not capable of describing nature as it is experienced, because its phenomenology, even at the most basic level, such as the interaction of charged particles, is an **emergent feature**.

The physics of many interacting constituents, **statistical mechanics**, has always been concerned with the study of macroscopic phenomena as an expression of some underlying microscopic physics. Contrary to particle physics, which makes use of very similar mathematical techniques, often both levels of physics, microscopic as well as macroscopic, are accessible to inspection. The wavy patterns forming in the sand as water runs off a shallow beach, can be studied at the small scale of the hydrodynamics of sand grains in water, as well as on the larger scale of channels interacting by the runoff. The study of **pattern formation**, a branch of statistical mechanics, is concerned with the mechanism underlying their emergence and how the physics at different length scales is related.

That phenomena on a large scale cannot be read off from their underlying, microscopic physics has been famously summarised by Phil Anderson as "**more is different**" (Anderson, 1972), *i.e.* the whole is more than the sum of its parts. In his article, Anderson challenged traditional reductionist thinking by confronting it with the desire to reconstruct the universe according to some theory of its microscopic structure. That seems plainly impossible and so, even when reductionist thinking leads us to believe that we "understand the universe", we are still unable to reconstruct it. Anderson pointed out that symmetries, at the very heart of every physical theory and often thought to prevail across all interaction, at a microscopic level can very different from the symmetries found at a macroscopic level. In the limit of large particle numbers, new symmetries may arise and, most strikingly, a symmetry might be **broken**. Long range, **cooperative phenomena** occur in systems which carry no (obvious) signature thereof on the microscopic scale. The most stunning example of such a phenomenon is probably superfluid helium, where a liquid, seemingly in defiance of gravity and the laws of thermodynamic, creeps over walls or forms a perpetual fountain.

Statistical mechanics and **many body physics** are both areas that study the structure and dynamics of matter or, more generally, many interacting degrees of freedom, and how new physics emerges from their interaction. As suggested by the word, it is normally implied that the emergent phenomenon is rooted in the microscopic interaction. One may call that view a reductionist take on emergence. After all, the emergent phenomenon is understood to be a product of the microscopic physics. Although caused by it, the emergent phenomenon may not be (readily) attributed to a particular feature. This view is normally referred to as **weak emergence**: The underlying cause for an emergent phenomenon and the precise mechanism that brings it about may not be known, but must ultimately be due to some basic, microscopic interaction. This take on emergence has been promoted most prominently by the physicist and Nobel laureate Laughlin Laughlin (2006).

Strong emergence on the other hand refers to phenomena appearing on a larger scale that are truly absent on the small scale. While this is difficult to square with traditional scientific thinking, classic examples are the human mind and its self-conscience, as well as the appearance of society and its structures. If strong emergence occurs, one may argue that conscience may appear on the level of society without their individual constituents being aware of it. Studies of eusocial insects (*e.g.* ants, bees) put this somewhat esoteric view in perspective.

As suggested above, the notion of emergence is not new to statistical mechanics. During the second half of the twentieth century, much of the theoretical effort was concentrated on the understanding of **phase transitions**. Phase transitions occur when symmetries get broken, *i.e.* systems that normally obey some symmetry, spontaneously favour a particular state. The paradigmatic example for such behaviour is the Ising Model. At high temperature an arrangement of elementary magnets (normally in regular lattices) displays perfect symmetry, *i.e.* each orientation appears equally frequent. As the temperature is lowered, the system **spontaneously** favours one particular orientation. At the point of the transition, the **critical point**, effective long range interaction takes place, *i.e.* the local interaction produces correlations across the lattice that are so strong that *none* of its parts can be ignored in order to characterise the overall, averaged behaviour. As a result cooperative phenomena emerge, the system acts as a whole.

The most successful theoretical description of phase transitions is due to the **renormalisation group** (Kadanoff, 1966). The basic idea is to capture some microscopic, local interaction by iterative **coarse graining**. Initially, the system might be represented by nearby basic ("atomic") constituents interacting according to some **couplings**. In the language of renormalisation, these are said to be **bare** couplings. The key idea of the renormalisation group is to split the system up into patches and to summarise the effect of the local interaction by introduction an effective, adjusted interaction of the patches. The patches are then taken to be the new basic constituents of the system. Once the interaction of the patches is expressed in terms of the couplings of the original system, the process of coarse graining can be iterated, until the overall behaviour is determined. This way, the renormalisation group arrives at statements of the form "the macroscopic behaviour of the original system with certain bare couplings equals that of the coarse-grained system with certain renormalised couplings". The renormalisation group therefore establishes an explicit link between bare and renormalised system, capturing the effect of coarse graining in the renormalisation of the couplings. A renormalised coupling describes "effective physics". For example, a charge surrounded by a cloud of opposite charges may be thought of as an effective, smaller charge with higher mass.

The spontaneous breakdown of symmetry resembles phenomena in particle physics and, possible more surprisingly, in biological systems. The most striking example is that of slime mould, which is a collection of single, individual cells that, under certain conditions, **organise** themselves into a a mesoscopic body which operates as a whole, not unlike primitive animals. At some stage, this "effective animal" can form a stalk and a fruiting body releasing spores, with the individuals in the former sacrificing their lives for the benefit of the latter. Given that the cells are genetically identical, a form of spontaneous symmetry (namely that of being identical) breaking must take place to allow the separation into stalk and fruiting body.

Large parts of statistical mechanics and, more generally, **soft condensed matter**, which studies any collection of degrees of freedom without considering their quantum nature, is concerned with the study and characterisation of "emergent phenomena", theoretically, as well as experimentally and computationally. Where this is applied to phenomena that traditionally do not fall within the realm of physics, the research is often labelled as **complexity**. The term refers to the presence of many entities, which normally interact in a microscopic, local way that is better understood than their collective behaviour and may be readily cast in the language of mathematics. Complex systems display emergent features, they evolve in time and (normally) keep changing.

The notion of renormalisation, coarse graining and effective interaction permeates the study of emergence in soft condensed matter and complexity. Although the formalism is difficult to adapt, the basic ideas carry over as the (emergent) behaviour on the large scale is derived from the microscopic behaviour on the small scale. Notably, renormalisation allows for and is sensitive to the generating of new effective interactions, that are not present originally. For example, plants cannot freely move on the soil, but a renormalisation scheme characterising their reproduction might signal effective, diffusive motion as plants may produce one offspring nearby before dying themselves, *as if* they had moved to the site of the offspring.

In summary, emergence has been studied in the realm of theoretical physics for more than a century. It can be thought of as the antidote of reductionism. The notion of emergence is integral to the field of complexity.

References

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