DIEP

handbook #1

DUTCH INSTITUTE FOR EMERGENT PHENOMENA

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WHY DO WE WANT TO UNDERSTAND EMERGENCE ?

The enormous success of developing and testing microscopic theories suggested that all of reality could be explained with a single fundamental theory: one may just break a piece of wood into its fundamental constitutents. This point of view was clearly expressed by many scientists.

In 1929, after some of the great successes of formulating the theory of quantum mechanics, Paul Dirac wrote: *The fundamental laws necessary for the mathematical treatment of a large part of physics and the whole of chemistry are thus completely known, and the difficulty lies only in the fact that application of these laws leads to equations that are too complex to be solved.*

In 1981, shorty after advances in string theory and supergravity, Stephen Hawking wrote in an article entitled “Is the End in Sight for Theoretical Physics?”: *I want to discuss the possibility that the goal of theoretical physics might be achieved in the not too distant future, say, by the end of the century. By this I mean that we might have a complete, consistent and unified theory of the physical interactions which would describe all possible observations.*

In 1995, after the successes of the standard model, Steven Weinberg wrote: *One can illustrate the reductionist world view by imagining all the principles of science as being dots on a huge chart, with arrows flowing into each principle from all other principles by which it is explained. . . they are all connected, and if followed backward they seem to branch outward from a common source, an ultimate law of nature.*

Time and history have shown that there is a recurrent thought in the imagination of scientists and philosophers alike, namely, that ultimately all scientific phenomena can be derived from a few fundamental laws of nature working behind the scenes at the microscopic level. But time and history have also taught us that many great scientists have underestimated the intricate and complex multi-level structure of reality. It is not surprising that this reductionist view of the world has been met with considerable oposition.

In 1972, Philip W. Anderson wrote: *The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.*

In 1972, Philip W. Anderson also wrote: *The behaviour of large and complex aggregates of elementary particles , it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviours require research which I think is as fundamental in its nature as any other.*

In 1999, Robert B. Laughlin and David Pines wrote: *So the triumph of the reductionism of the Greeks is a pyrrhic victory: We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance.*

In 2003, Piers Coleman wrote: *To understand how crystalline assemblies of gold atoms acquire the properties of metallic gold, we need new principles– principles that describe the collective behavior of matter when humungous numbers of gold atoms congregate to form a metallic crystal.*

It is equally unsurprising that those strongly opposing the views of Dirac, Hawking and Weinberg were condensed matter physicists. Emergent collective behaviour arises in many circumstances due to the complex interaction of many fundamental constituents. This behaviour is extremely difficult to understand/explain using the corresponding microscopic theory. In addition, the fact that emergent behaviour does not strongly depend on many of the details of the microscopic theory leads to the separation of science into distinct branches with no apparent connection. Therefore each science follows a pragmatic approach and attempts to reach its own "fundamental laws" and from there understand the emergent phenomena they sought to explain.

It is the case, therefore, that the apparently opposing views shared by the scientists mentioned earlier are not actually mutually exclusive. The majority agrees that a piece of wood is composed of fundamental constitutients whose behaviour is described by some lower-level fundamental theory but to describe the collective motion of all the constituents forming the piece of wood with that same fundamental theory is something quite non-trivial.

However, a lack of understanding of emergent phenomena in terms of an underlying microscopic theory leads to a fragmented view of science and no real in-depth understanding of the phenomena. To make progress, experimentation usually takes a prominent role. Perhaps one of the best examples is that of the incompletness of classical mechanics that lasted for many years. In fact, it took 200 years after Newton and Leibniz for the concept of energy in classical mechanics to acquire physical meaning. Once Benjamin Thompson showed that heat is produced as a canon is bored, it did not take long to realise that energy in classical mechanics is an emergent property of random thermal motion.

It is unnecessary to discuss the importance of understanding heat, energy conservation and the developments that this understanding led to.

Emergent behaviour in the majority of modern contexts indicates the existence of a barrier in our knowledge of the complex multi-level structure of reality, but not an insourmountable one. Instead, breaking such barriers leads to major advances in science.

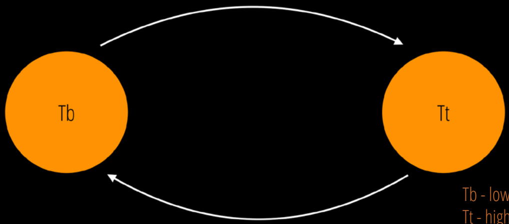
How do we explain the emergence of gravity? The appearance of topological phases of matter, of high temperature superconductivity? Of self-assembly in colloids? The emergence of the classical world from quantum theory? The emergence of thermodynamics? Of organised behaviour in non-equilibrium systems? Of nucleation, shape morphing and protein folding? The emergence of galaxy formation? The emergence of symmetries in particle physics?

These and many other questions are the reason why we need to understand emergent behaviour: the main task that DIEP has to perform.

WHAT IS THE SCIENCE OF EMERGENCE ?

The universe is composed of microscopic building blocks and the world we see around us is the result of a combination of millions of billions of billions of those blocks. When we walk through the streets of our cities, we do not see these microscopic elements of the universe but instead cars and buses smoothly driving by us. If we would carry our microscopes and particle accelerators with us, we would be able to see some part of that microscopic world but we usually carry nothing more than a pair of Ray-Ban glasses. The world we see with our own eyes is governed by laws that originate from a microscopic world but the laws that govern that microscopic world are completely different. The world we experience is said to have emerged from a world that only microscopes can reach. All the smooth experiences of wind blowing, music, sound or touch are the result of these emergent laws.

Between the microscopic world, where the fundamental building blocks of matter reside, and the macroscopic world that we see around us, there is a very large number of other worlds (or scales) that also emerge from that same microscopic world. These are, for example, the electronic scale, the atomic scale, the molecular scale or the mesoscopic scale. All these scales can be approached by different disciplines. Research in emergent phenomena is based on a translational process from a lower level of description (world/scale) to a higher level of description or vice-versa, i.e. understanding emergent phenomena or emergent theories requires establishing a dictionary between a theory and its emergent phenomena or between two theories, one of which emerges from the other.



Tb - lower level description
Tt - higher level description

There are many examples of emergence around us and in physics, mathematics and chemistry. These include the emergence of Newton's laws from quantum mechanics, the emergence of the heat equation for the collective motion of molecules, the emergence of thermodynamic phase transitions from microscopic statistical systems, the emergence of Van der Waals forces by coarse-graining the interactions of neighbouring molecules, the emergence of new phases of matter such as unconventional superconductivity, the emergence of new spontaneous behaviour such as self-assembly in polymers, criticality and self-organisation in active matter, and the emergence of gravity from holographic field theories such as in the context of the AdS/CFT correspondence and string theory. Emergent phenomena in different areas is often remarkably similar leading to theories with similar structures at very different scales. Cross-fertilisation of similarly novel concepts across the different disciplines will indubitably propel science forward in the 21th century.

Emergence establishes a relationship between theories or between effective descriptions at different levels of reality. When two descriptions meet, expertise of the two descriptions is required in order to properly understand emergent phenomena. This is why DIEP is a broad interdisciplinary research centre spanning several of the fundamental sciences.

WHAT IS EMERGENCE ?

The answer to this question is found in the context of philosophy of science where the concept of “emergence” is continuously refined and tested against different situations in physics, chemistry and mathematics. The usage of the term first appeared in the context of philosophy of mind but was later taken by philosophy of science to describe phenomena that arose due to the collective and often complex behaviour of microscopic constituents. Despite many modern notions of “emergence” being in place and no overwhelming consensus existing amongst scientists and philosophers, DIEP has chosen to use the following pragmatic, inclusive and moderately subjective definition of emergent phenomena:

Emergent phenomena is behaviour that is novel and robust relative to some comparison class. (introduced by J. Butterfield)

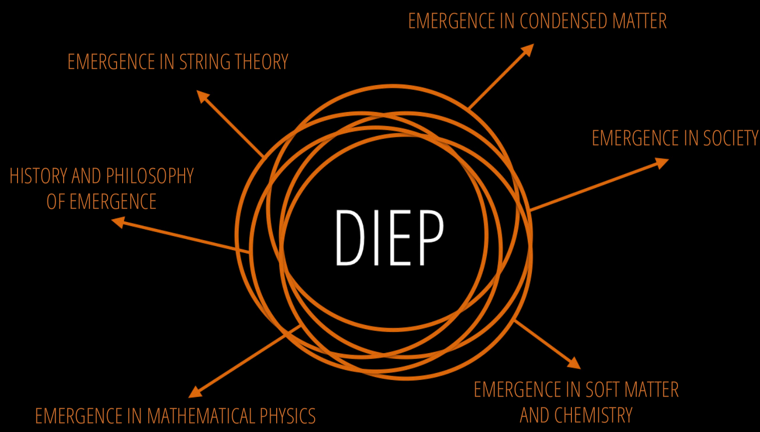
The term “emergent phenomena” in the definition above can also be replaced by “emergent theory” leading to a definition of “emergent theory”. To quickly grasp some aspects of this definition, one may think of novel collective behaviour when compared to the microscopic constituents of a system (the comparison class) or of novel behaviour that appears when taking a specific limit of a whole family of systems. For instance, certain polymers can self-assemble forming bigger structures that exhibit new morphologies and topologies. This type of behaviour is new when compared to the behaviour of individual elements of the system and it is also robust in the sense that it doesn’t depend on all the attributes of the individual polymers.

Similarly, if one thinks of the emergence of thermodynamics from statistical systems, macro notions such as temperature are not definable for individual molecules in a gas and at the same time are robust, as they are largely independent from the individual molecules' size and velocity.

The notion of "novelty" characterises "emergence" since "to emerge" means something new and non-trivial that arises from a given theory, either by some form of coarse-graining/fine-graining or by taking a specific limit. In this context, for example, one may speak of new laws or new behaviour of large-scale objects when compared to the behaviour of the individual constituents. The notion of "robustness" means that the phenomenon has a certain degree of independence from the comparison class, in most situations implying that the behaviour is not easily obtained from the theory describing the microscopic constituents or that the behaviour is obtained by a non-trivial limit of a class of systems.

Though already made explicit, it is important to stress that emergence does not always involve coarse- or fine-graining , it can also arise as a limit of a class of systems such that at that limit there is novel and robust behaviour. A classic example is the emergence of Newtonian physics from quantum mechanics when the number of particles involved is taken to be very large or when Planck's constant is taken to be zero. This possibility enlarges the scope of approaches to the understanding of emergent phenomena.

The abstract definition of emergence introduced earlier requires concrete examples. In the next few pages, we have collected a few and brief examples, organised into classes.



HISTORY AND PHILOSOPHY OF EMERGENCE

The modern usage of the term “emergence” was first introduced by the philosopher G.W. Lewes in the context of philosophy of mind. The term quickly spread to other parts of philosophy and science and expressed the belief of many that sciences such as chemistry, biology or psychology were described by fundamental laws and properties widely different from those of their supposed small constituents, as studied by physics. C.D. Broad, one of the so called “British emergentists” in the early 1900’s, was particularly interested in the laws of chemistry and how they greatly differed from the laws of physics. He believed that the combination of certain chemical substances required the introduction of specific laws beyond the general laws of combination applicable to all substances. However, with increasing scientific advances, the examples studied by Broad were in fact shown to be reducible to the laws of physics. With the success of reductionism (that higher level theories are ultimately reducible to lower level ones such as physics), the role of emergence was continuously pushed to higher level sciences (such as psychology) until the emergentist movement effectively died.

The debate on emergence and emergent properties in the philosophical/scientific context was revived by the 1972 paper of Nobel prize winner and condensed matter physicist Philip W. Anderson, More is Different. His opinion is largely shared by several others of his peers, including Robert Laughlin, David Pines and Piers Coleman. In this paper, Anderson argues that the laws of condensed matter systems are as fundamental as the laws of high energy physics (such as those governing the standard model) though still agreeing with the doctrine of microphysicalism, by which all such systems are made of microscopic constituents governed by microscopic laws. However, he argues that even though all matter is reducible to microscopic building blocks, it does not follow from there that one can derive all the workings of the universe. It may be theoretically possible to derive macroscopic laws from microscopic ones, though perhaps not practically possible. Behind the curtain, Anderson's reasoning stems from examples in condensed matter physics where large aggregates of microscopic building blocks do not exhibit the same symmetries and laws as those of the underlying microscopic theory. In most cases, spontaneous symmetry breaking (as in solid crystals) occurs, and the governing laws are difficult, if not impossible, to understand in terms of the natural variables/parameters used to describe the microscopic theory.

This revival of "emergent philosophy" led to many developments and refinements of the concept of "emergence" itself. Some of these philosophical explorations led to metaphysical considerations of the notion of emergence, novelty and reducibility. Jaegwon Kim, in the context of philosophy of mind, believed that emergence involved higher levels of complexity, unpredictability and irreducibility. Batterman, in the context of philosophy of science, believed that emergence required a limiting and singular behaviour, such as the appearance of divergences in the free energy when the limit of a large number of particles (thermodynamic limit) is taken in statistical mechanics systems. Butterfield, in turn, claims that emergence and reduction (interpreted as deduction) are mutually independent and that emergence can occur in non-singular limiting behaviour. The notion of emergence is still currently being refined and tested against many new contexts within science.

EMERGENCE IN STRING THEORY

String theory provides many examples of emergent behaviour but perhaps the most surprising case of emergence is that of the emergence of gravity itself, and thus of spacetime. Despite being a very active research field, and hence being in continuous development, there are multiple indications within the framework of string theory that gravity is an emergent phenomenon, such as mirror symmetry, topology change transitions and many non-perturbative dualities.

One of most well studied examples of these dualities is the so-called AdS/CFT correspondence, which is a holographic duality relating a conventional quantum field theory (without gravity) living in the boundary of Anti-de Sitter space to a theory of quantum gravity living in one higher dimension in the bulk of that same space. In this context, gravity and spacetime are thought to emerge from the local degrees of freedom that characterise the conventional boundary quantum field theory. There are several examples where the emergence of space can be made explicit. In particular, the renormalisation group flows of the quantum field theory (determining the physics at a given energy scale) can be interpreted as the emergence of the bulk holographic coordinate, in turn responsible for the non-trivial curvature of the bulk spacetime.

Ideas that originated in the study of non-perturbative dualities have been applied to other contexts, including to astrophysics using the so called Kerr/CFT correspondence, which exploits the fact that the Kerr black hole is characterised by an emergent conformal symmetry when it is spinning very fast.

EMERGENCE IN CONDENSED MATTER

Condensed matter physicist Philip W. Anderson had a tremendous influence on the resurgence of emergent philosophy in science. One of the main reasons for this is that condensed matter systems are large enough systems (i.e. composed of a large collection of microscopic constituents) to exhibit a wide range of emergent collective behaviour, which is extremely difficult to understand by using the quantum mechanical theory of its microscopic constituents.

For many years, emergence in condensed matter was focused on strongly correlated electron systems - systems in which the Coulomb interactions between electrons are always strong and important. Strongly interacting, or strongly correlated, electrons often lead to many almost degenerate (or at least rather finely balanced, energetically) ground states of the system, so that relatively small changes to the electronic environment induce phase transitions into phases associated with the collective behaviour of the electron system. Examples of these emergent phases include (unconventional) superconductivity, various novel magnetic phases, and strange metallic states that do not obey the standard Landau Fermi liquid theory.

During the past few years, new types of emergent phases have been discovered experimentally. A crucial difference between emergent topological phases and the emergent phases in correlated electron systems mentioned above is that topological order is non-symmetry breaking. One well-established example of topological order is the fractional quantum Hall phase, whose appearance is not delineated by an order parameter, but by by the development of long-range quantum entanglement. Gapped spin liquids and skyrmionic states are more recent examples of topological phases, as are topological insulators.

EMERGENCE IN MATHEMATICAL PHYSICS

Classical and quantum mechanical laws are time reversible. For instance, the collision of two particles looks exactly the same if we move forward or backward in time. However, the world we see around us is obviously irreversible: there is an arrow of time. We see the sea waves approaching the shore and breaking but we do not all of a sudden see the waves rolling backwards and disappearing. Thermodynamically speaking, there is a law that tell us that the universe conspires in such a way that entropy always increases. How can macroscopic irreversibility be reconciled with microscopic reversibility? Boltzman himself, using probability theory, showed that irreversibility emerges for a gas of molecules by taking a singular limit, under apropriate initial conditions, where the number of particles in the system diverges.

The world we see around us is also mostly classical, but microscopic laws at the atomic scale are governed by quantum physics. Quantum physics has a certain degree of indeterminacy: a particle may be in a superposition of different states, which, by virtue of Heisenberg's Uncertainty Principle, does not allow us to extract both the position and velocity of the particle with equal precision. However, once billions of particles are put together and observed at macroscopic scales, classical physics emerges, as well as deterministic measurements of the properties of macroscopic objects. Traditional methods for understanding this type of emergent phenomenon rely on the so called WKB approximation, which, however, is only applicable to certain cases. A more powerful mathematical approach is (strict) deformation quantisation, which involves the machinery of C* algebras. Within this context, Planck's constant is a real number that can be formally varied and when taken to zero leads to the emergence of classical physics.

EMERGENCE IN SOFT MATTER AND CHEMISTRY

Soft matter and chemistry involve systems of billions of billions of microscopic constituents that exhibit a wide variety of emergent behaviour occurring at multiple scales, which is extremely difficult to track down in terms of the microscopic theory. A simple example is the difficulty in predicting the shape of different molecules using quantum mechanics, in particular pyramidal molecules, due to symmetry breaking. Small molecules, such as these, already require new emergent laws and principles to be discovered. The case of larger molecules such as polymers and biomolecules is even harder to predict.

Because of the difficulty in understanding the microscopics of systems such as colloids and polymers, which ultimately constitute the building blocks for biological life, active research in soft matter is constantly informed by heavy numerical simulations and experiments. To make theoretical progress in these areas, techniques for coarse-graining take a prominent role. The complicated interactions between building blocks can be replaced by effective interactions between larger assemblies e.g. nano particles, if all other degrees of freedom are unimportant. These forces can be seen as emergent. A classic example is the integration of short-range molecular van der Waals forces between colloids, which ultimately allow geckos to climb smooth walls. In multi-scale numerical simulations, coarse-grained models are used to simulate regions of parameter space for which less detail is needed, while other regions where finer detail is required make use of the microscopic model.

EMERGENCE IN SOCIETY

Emergent behaviour often arises as collective behaviour due to the interaction of many fundamental building blocks. This type of behaviour is also observed in animal and human societies and can be approached using the same mathematical tools which are used in the different scientific disciplines. Curious and widely observed phenomena are the organised behaviour of bird flocks, schools of fish and herds of sheep at macroscopic scales and the organised behaviour of bacteria and enzymes at mesoscopic scales. The emergence of collective behaviour in animal societies has direct consequences for the prediction of global catastrophic events such as earthquakes, volcanic explosions, disease spreading and sudden weather changes. These types of emergent phenomena requires the understanding of non-equilibrium statistical mechanics.

Several systems in human societies also exhibit self-organised emergent behaviour that can be modelled by phenomenological theories of critical phase transitions, allowing prediction of the so called tipping points at which the system changes abruptly from one state to another. These systems include the emergence of traffic jams, the spontaneous systemic failures of the human body (asthma attacks, epileptic seizures), financial market crashes and abrupt changes in climate or of certain wildlife populations. The reason why such theories can be broadly applicable is because this type of emergent behaviour is robust and insensitive to many of the different properties of the microscopic constituents (i.e. to all the specific details of birds or human beings).

QUESTIONS THAT DIEP WOULD LIKE TO ANSWER

Non-equilibrium statistical mechanics for driven systems?

Is there a general theory for quenched or annealed disorder in physical systems?

What are the common features between multiscale models in different disciplines?

When and how do new symmetries emerge at low energies/long wavelengths?

What are the relevant coordinates or length/time scale to coarse grain in?

How to coarse-grain microscopic theories, and how to reverse map from coarse levels to underlying levels?

How can we better understand symmetries and symmetry-breaking?

How can understanding emergence help us to design useful materials?

How can control over emergent materials be achieved?

For which microscopic quantum systems is the low-energy/long-wavelength dynamics described by an emergent gravitational theory?

What do theories of self-organization have in common?

How do conventional methods such as the Born-Oppenheimer approximation and the renormalization group fit into this framework?

Which phases of matter admit gravitational descriptions? Which emergent properties of matter can be studied using gravitational field equations?

How do we reconstruct the corresponding space-time geometry?
What is the role of quantum information theory?

Cat state experiments in quantum mechanics? Flea-perturbation induced collapse?

Do all features of classical chaos, dynamical systems, attractors and KAM theory have quantum counterparts?

Can we find a unifying description of emergent behaviour?

Is there a classification of topological states of classical matter? Do these systems have interesting applications?

Can we develop a self-contained and overarching categorisation of emergent phenomena (epistemic/ontological)?

DIEP VISITORS PROGRAMME

DIEP aims at promoting interactions between researchers and scientists whose research focuses on emergent phenomena. For this purpose DIEP awards travel grants to interested groups. In order to apply for funds send an e-mail to info@d-iep.org with a description of the scientists involved, the research purpose in line with DIEP as well as an estimated cost.

Jeremy Butterfield (U. Cambridge)

Dates: 20th-23rd June 2018

Location: UvA | Host: Jeroen van Dongen

Jeremy Butterfield is a distinguished philosopher of physics, a senior research fellow at Trinity College, Cambridge, a fellow of the British Academy, and a past President of the British Society for the Philosophy of Science. Jeremy has worked extensively and made significant contributions to the philosophy of emergence.

Jeremy will be giving a DIEP seminar on dualities and emergence on June 22nd.

Vijay Balasubramanian (U. Penn)

Dates: 24th-26th May 2018 | Location: UvA

Host: Jan de Boer

Vijay has two scientific lives: he works on string theory by day and on biophysics by night (or the other way around, no one actually knows!). In any case, his research in string theory, black holes and quantum information theory has led him to establish his own group in biophysics which applies information theory to neural networks and the brain. On May 24th, Vijay will be giving an IoP colloquium and on May 25th, Vijay will be giving a talk at the route community building day.

Jemal Guven (UNAM)

Dates: 28th May-4th of June 2018

Location: UvA & Leiden

Hosts: Jay Armas & Luca Giomi

Jemal works in between mathematics and biophysics. He has done extensive and significant work in the geometry of fluid membranes, surface deformations and their applications to biomembranes, Helfrich functionals and soft matter.

DIEP: WHAT AND WHO?

The Dutch Institute for Emergent Phenomena (DIEP) is an interdisciplinary research centre across fundamental sciences with the purpose of furthering the understanding of emergent phenomena. It aims at understanding how the universe, space, time and the fundamental building blocks of matter emerged from the quantum world and how these building blocks aggregate to form the nano, molecular and polymeric structures that ultimately give rise to the macroscopic world we experience today. Emergent phenomena are extremely common in nature and their manifestation is based on the same underlying principles across sciences. Using analytic, numerical, experimental and philosophical methods available from quantum gravity, mathematics, physics, chemistry and philosophy of science, DIEP takes a transdisciplinary approach in tackling emergent behaviour.

Integrated in the National Science Agenda (route 2), DIEP will gather research groups and scientists across the Netherlands and beyond and establish itself as a beacon for a new understanding of nature and emergence. During the period 2018-2020, DIEP will bring together scientists, researchers and scholars in the Netherlands via a regular visitors programme and a series of interdisciplinary workshops which will foster new collaborations and provide a road-map for a new research center. Research groups can become associated with DIEP and apply for travel grants via its visitors programme.

Jan de Boer

Quantum gravity, string theory

Klaas Landsman

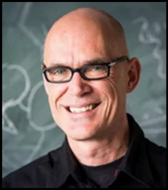
Mathematical physics, philosophy of physics

Mark Golden

Quantum matter

Alix McCollam

Condensed matter



Willem Kegel

Soft matter

Peter Bolhuis

Computational chemistry

Jácome Armas

String theory, coordination and communication

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