DRS BOGDAN HNAT & TOBIAS GALLA

Nothing left in the balance

Dr Bogdan Hnat of the University of Warwick and **Dr Tobias Galla** of the University of Manchester unveil Network Plus, a project designed to maximise the UK's competitiveness in the field of non-equilibrium physics

Can you explain what is understood by 'far-from-equilibrium' or 'non-equilibrium' physics?

TG: Equilibrium systems do not evolve in time. A classic example is that of a fluid in a container separated from all external influences. With no mass or energy fluxes, it will reach its equilibrium and remain in this state. Traditional physical theories, such as thermodynamics, have been very successful in describing systems in equilibrium. Now, consider the same drum of fluid placed on a heated plate, such that a large difference in temperature can exist between its bottom and top. A non-equilibrium quasi-stationary state will emerge, where large-scale flows, so-called convection cells, will emerge and try to suppress the temperature difference. Most real physical systems, which are out of equilibrium, are strongly coupled to their environment and may exhibit inherently nonlinear responses to small perturbations. These systems change over time, are driven by external factors and never truly equilibrate. Examples of other systems far from equilibrium include the Earth's atmosphere, biological systems and traffic flows.

With this in mind, what is Network Plus and what does it aim to achieve?

BH: The Network aims to prepare the UK community to meet the challenge in advancing the field of non-equilibrium systems and to ensure the UK community's international competitiveness as a collective. No single discipline can address, and successfully answer, the open questions related to the emergence and physics of systems far from equilibrium. Our objective is to use the existing but scattered expertise in the UK to collectively identify the problems that UK research community should focus on in the near future.

By definition, study of non-equilibrium systems covers a broad range of topics within physics. How important is the promotion of collaboration within the Network?

TG: Collaboration is crucial in most areas of research, and especially so in this field, which is very broad in scope. The idea of the Network is to get researchers out of their comfort zone, and encourage them to interact either with others who might be using similar tools and methods, but applied to other problems, or with those who have a different viewpoint on how to make progress on a particular question. This is the key element of the Network. The need for interaction is amplified by the fact that emergence and non-equilibrium dynamics have applications in a number of disciplines other than physics. Physicists will never be able to make a real difference to economics if they do not talk to economists, for example.

Can you highlight any tangible impacts that research in these areas has already had?

TG: Ideas from non-equilibrium physics have fed into a range of applications outside physics. One concrete example is in models of vehicular traffic, which are being used to inform intelligent traffic light systems and cruise control mechanisms. Closely related, individual-based models of pedestrian motion are being used to design football stadiums or other sites visited by large crowds. In economics, out-of-equilibrium models are being proposed by an increasing fraction of economists, and many of these models have benefited from input and ideas from non-equilibrium physics. Other examples include the rheology of fluids in industrial processes.

How does the UK compare internationally when it comes to work in this area?

BH: In an EPSRC survey, 58 per cent of participants indicated the lack of world-leading expertise in this area in the UK. However, this could simply be a reflection of how fragmented research of systems far-from-equilibrium is. Our Network activities show that physics, mathematics and engineering departments in nearly all leading UK universities conduct research in this area in some form. What is currently missing is the broader stage for these experts to contribute to a wider development of this field, and thus be recognised as national and international experts. The Network will help us bridge this gap.

Three-pronged approach

The Network focuses on three cross-disciplinary themes, which represent common aspects of systems far from equilibrium. These are:

- Formation of structures and patterns, including self-assembly in biology, exotic quasi-particles in quantum systems or zonal flows in plasmas or the atmosphere
- The dynamics of large-scale failure in diverse systems, such as stock markets, epidemics, earthquakes and magnetically confined plasma
- Responses to strong driving forces and shocks: for example turbulence in pipe flow, rheology of soft materials and driven quantum systems

Confronting emergence and far-from-equilibrium systems

The **EPSRC Network Plus** is bringing together a diverse range of fields to advance understanding of emergence and far-from-equilibrium systems, which represent the richness of life on Earth and hold substantial promise for future technologies

NEARLY ALL NATURAL phenomena are examples of physics far from equilibrium. Indeed, the world around us is not merely a set of disconnected, isolated components; rather, these elements interact, are driven and can lose energy at various scales. Although equilibrium states have been the focus of research for over a century, much of the splendour of natural systems comes from conditions which are far-from-equilibrium: from the nanoscale molecular processes which form the basis of life itself, to the dynamics of climate on Earth.

The energy that reaches the Earth from the Sun keeps the Earth's atmosphere out of equilibrium, contributing to generation of complex weather patterns and to the diversity of life. Interaction with the surrounding environment underlies the degradation of manmade structures. The shocks to financial infrastructure can be partially attributed to patterns in information exchange between individuals and institutions. Turbulent far-from-equilibrium flows are important for inkjet printing, and in nuclear fusion plasmas. In addition, a key notion in (and beyond) contemporary physics is that of emergence – that is, the generation of large-scale structures from interactions of the individual components at the microscale. As the Nobel laureate P W Anderson put it, 'more is different'. Collections of many particles behave in ways that cannot be anticipated by studying them individually, as we see in phenomena raging from superconductivity to living organisms.

Far-from-equilibrium behaviour is common in classical and quantum physics, and extends beyond to social science and economics. Gaining a better understanding of non-equilibrium systems is crucial due to its direct impact on manufacturing, the economy and climate. It represents largely unchartered territory, so the potential for scientific breakthroughs is vast.

CHALLENGES FOR PHYSICISTS

Far-from-equilibrium processes are forcing physicists to rethink the foundations of current theories and experiments. There are two important themes in this field: the ubiquitous nature of features associated with non-equilibrium behaviour, and how little we know about it. Non-equilibrium features are relevant beyond the traditional boundaries of physics, for example in biology, the social sciences and economics. Because its relevance is so broad, research into far-from-equilibrium processes requires communication between physicists, biologists, chemists, mathematicians, economists and engineers. On top of this, there is no established theoretical framework for systems out of equilibrium, which poses a significant problem.

Despite these difficulties, modern physics is well placed to lead progress in this area. It has long practised approaches that bring together ideas from diverse scientific disciplines. For example, condensed matter physics studies of strongly correlated systems have provided a legacy of fundamental models and organising principles. These successes have motivated researchers to search for similar organising principles in far-from-equilibrium phenomena beyond the traditional boundaries of physics. Since some condensed matter phenomena, such as high-temperature superconductivity, are still not explained, the exchange of ideas may bring mutual benefits. Searching for commonalities in massively disparate systems is perhaps physics' greatest asset.

THE EPSRC NETWORK PLUS

Achieving progress in this field will require time and the collective action of researchers across a range of disciplines. Dr Bodgan Hnat at the University of Warwick and Dr Tobias Galla at the University of Manchester are coordinating the Engineering and Physical Sciences Research Council (EPSRC) Network Plus on Emergence and Physics far-from-equilibrium, which aims to bring together the appropriate expertise, focus on the relevant challenges and determine the most promising research strategies to address these challenges.

The EPSRC has committed £250,000 to the Network, and believes that supporting the research community to work together will accelerate major breakthroughs and will help to make the UK a world leader in non-equilibrium physics over the next decade or so. The Network already represents a significant proportion of the UK research base and involves key figures in industry. At the same time, it is growing and evolving; the number of participating institutions continues to increase and the Network's foci are continually developing. The Network has also established a link with the Institute for Complex Adaptive Matter (ICAM-

INTELLIGENCE

TOWARDS CONSENSUS ON A UNIFYING TREATMENT OF EMERGENCE AND SYSTEMS FAR FROM EQUILIBRIUM

OBJECTIVES

To bring together the UK community to identify key barriers; to unearth hidden potential for novel collaborations and to develop the most effective research agenda; to establish a roadmap towards progress exploiting the full potential of the UK research base; to raise public awareness; and to promote interaction with industry.

FUNDING

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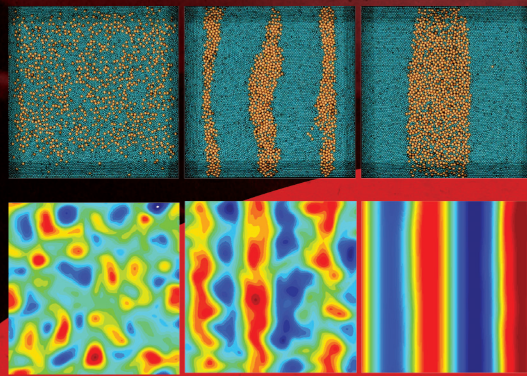

Example of structure formation and pattern emergence in granular matter (**top**: images courtesy of Tom Mullin and Draga Pihler-Puzović) and plasma turbulence (**bottom**: images courtesy of Bogdan Hnat). While the underlying physical processes are different in those systems, the final state is that of zonal bands.

J M Dewhurst; B Hnat; R O Dendy, Finite Larmor radius effects on test particle transport in drift wave-zonal flow turbulence, Plasma physics and controlled fusion, ***52****, 2010*

I2CAM), a worldwide network of over 100 leading centres of complex materials research.

ENCOURAGING COLLABORATION

The challenges in non-equilibrium science are also its strengths. The area represents many diverse fields, often separated by specific terminology and methodology – an obstacle the Network hopes to overcome. However, the variety of the field also enables analogies to be drawn between very different phenomena, which can be used to address specific problems and develop general principles. The objective of the Network is to work towards a consensus within this diverse community on a unifying treatment of emergence and systems far-from-equilibrium.

The Network plans to utilise the UK knowledge base to identify the areas of research that should be focused on, and to find the most promising approaches to tackle these challenges. In order to achieve this, it coordinates activities designed specifically to promote collaborations across different disciplines. Annual General Network Discussion Meetings are the main forum for refinement, evolution and consolidation of the objectives and outcomes. Focus Workshops provide opportunity for showcases of particular approaches and methods with a prospect of application across different research areas. Additionally, the Network will provide funding for collaborative pilot projects, with an emphasis on solving the real-world problems in collaboration with industrial partners.

SCIENTIFIC THEMES

There are three key scientific themes at the crux of the Network: the spontaneous development of structure and patterns, the dynamics of large-scale failure, and the response to strong driving and shocks. These themes are inextricably linked to concepts emergence and non-equilibrium dynamics, and apply as much to condensed matter physics as they do to phenomena beyond the conventional realms of physics.

From the fractal structure of snowflakes and crystals to biological self-assembly and community formation in social networks, pattern formation and spontaneous ordering are classic examples of emergent phenomena. In the spirit of the Network's objectives, emergence in classical and quantum systems will be discussed and compared in order to identify the most promising avenues for future research. Emergence is not unique to non-equilibrium physics and is central to the study of strongly correlated systems, both quantum and classical. For instance, exotic quasi-particles emerge in topological phases of matter, magnetic monopole excitations govern magnetic relaxation properties in frustrated magnets and novel phase transitions appear in driven quantum liquids.

The dynamics of large-scale failure are also being studied. While the sudden fracture of materials under strain is of obvious interest to industrial applications, similar behaviour appears in earthquakes, stock market crashes, tipping points in social dynamics and in the spread of epidemics. In a different context, sudden changes to the parameters of a quantum system lead to non-equilibrium processes significant to quantum computing. Common mathematical structures underlie these diverse phenomena and will be explored by the Network, with a focus on characteristic correlations, which could be used to warn of impending systemic failure.

Complex emergent behaviour often arises from systems with strong external forcing. Related to this is the response of a complex system to sudden shock. This has clear practical implications for man-made systems. For example, the behaviour of electrical and computational networks and their response to breakage or failure of links is of great interest to industry. There is no framework for calculating responses for far-from-equilibrium situations – a knowledge gap the Network will help to close.

TOWARDS CONSENSUS

Far-from-equilibrium systems give rise to the rich diversity of Earth, but they are also hugely important to technology, including nanoscale electronics, so breakthroughs in the field have the potential for far-reaching impact. Because these phenomena are so ubiquitous and form the basis of many of society's concerns – from the economy to climate – a better understanding of these processes holds great promise.

Reaching a consensus on what the most promising approaches are for academic research and applications in industry is a challenging goal. A number of events are being planned for 2014, covering a range of aspects in non-equilibrium systems, and focusing on initiating multidisciplinary collaborations. These activities, together with further events in 2015, will propel the community towards a roadmap identifying the most promising future research strategies beyond the lifetime of the EPSRC Network Plus.