The Second International TRANSIT Workshop on Cross-disciplinary Research

Emergence

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Ron Cooke Hub, University of York, UK

Programme and Abstracts

UNIVERSITY of York

hosted by YCCSA :
York Cross-disciplinary Centre for Systems Analysis

Wed 27 March 2019

09:15 *registration / coffee*

09:45 Susan Stepney: Welcome to TWCR 2019

10:00 keynote 1 -- Liz Varga

"Abstracting emergence in living beings to demonstrate two types of weak emergence using simple models"

11:00 *coffee*

11:30 Namid Shatil, Sabine Hauert: "Engineering Emergence at the Nanoscale: How nanoparticle design offers a new tool in the fight against cancer"

12:00 Curtis Palasiuk, Andrew Chantry, Dawn Walker: "Emergent Homeostasis: An Agent-Based Coupled Bone Remodelling and its Disruption"

12:30 David Kirkham: "Emergent learning affordancies of an out-of-class language learning modality"

13:00 *lunch*

14:00 Ron Cottam, Willy Ranson, Roger Vounckx: "Rules for Metastatic Emergence"

14:30 Janine Illian, James Bown: "Quantifying emergent spatial patterns: an application in cancer"

15:00 Carlos Morales-Garduno, Lisa Thurston, Dawn Walker, Alireza Fazeli: "The role of Cell-level interactions in emergent behaviour in the fertilization process in pigs; a highly parallel Agent-Based Model using FlameGPU"

15:30 *tea*

16:00 keynote 2 -- Rebecca Mancy

"Emergent clustering of species traits as a driver of biodiversity"

17:00 panel discussion

18:00 close

Thur 28 March 2019

08:45 *registration / coffee*

09:00 keynote 3 -- Yasmin Merali

"The note you play ..."

10:00 John Forrester: "How structured outputs help us see emergent properties of social and political knowledge systems"

10:30 Kerry Turner: "Climate Change: A Catalyst for Human Emergence (Systems Thinking to Save the World)"

11:00 *coffee*

11:30 Tom Mcleish, Tom Lancaster, Mark Pexton: "Emergence and Topological Order in Classical and Quantum Systems"

12:00 Martin Trefzer, Matthew Rowlings: "Emergent properties of bio-inspired hardware"

12:30 Simon Hickinbotham, Susan Stepney, Paulien Hogeweg: "Emergence in a Replicator-Parasite Automata System"

13:00 *lunch*

14:00 Wolfgang Banzhaf and Roger White: "Strong Emergence and Creative Systems"

14:30 Ana Teixeira de Melo and Leo Caves: "Complex Thinking and Emergence"

15:00 Ana Teixeira de Melo and Leo Caves (facilitators): "Relational Thinking For Emergence" guided discussion

16:00 panel discussion

16:30 *tea / close*

Abstracting emergence in living beings to demonstrate two types of weak emergence using simple models

Liz Varga, J. M. Gonzalez de Durana, P. M. Allen

When examining emergent phenomena in nature and especially in living beings we observe some basic characteristics of emergence: open systems, networks and symmetry (breaking). Based on these observations, we extend existing notions of weak emergence into two types: true weak and almost hard. We develop a simple model and propose that true weak emergence occurs when the system is invertible, that is, if we know the output of a system, then its input can be determined. We define almost hard emergence as the phenomena where algorithms representing a system cannot be inverted.

Engineering Emergence at the Nanoscale: How nanoparticle design offers a new tool in the fight against cancer

Namid. Shatil[1], Sabine Hauert[1]
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Studying the mechanisms that lead to emergence increases our ability to recreate these complex behaviours. This is particularly true within nanoscience, where appropriate bio-mimetic design of nanoparticles (individual nanometer-sized particles) can lead to incredibly rich emergent behaviours that include self-assembly and disassembly, co-ordination, and even self-replication of the aggregated particles[1–3].

Nanoparticles have a strong potential for use in medicine both as diagnostic tools and as drug-delivery vectors. This is partly due to their small size and effective coating, which allows them to contain molecules that are only released under certain binding conditions. However, their potency is dramatically increased when nanoparticles are specifically engineered to initiate and maintain complex emergent behaviours. Global (cell-scale or tissue-scale) cooperative behaviour can be initiated either through external stimuli (such as electromagnetic waves[4]) or internal stimuli (such as naturally occurring molecules or other nanoparticles[5,6]) which occurs at the local (nanoparticle) scale. All these factors combine to make nanoparticles an exciting avenue for biomedical research.

This is particularly true within cancer research where nanoparticles are able to overcome traditional bio-barriers such as poor transportation through the vascular, tissue penetration at the tumour site and endocytosis. Recent advances in applying a multiscale systems approach to cancer has also raised the possibility of using nanoparticles to prevent or contain the hallmarks of cancer such as rapid growth or metastasis[3]. In this presentation, we will describe the steps required to engineer emergent behaviour occurring across billions on nanoparticles. We will then couple this with a multiscale computational model of tumour growth. This demonstrates how our understanding of emergence is motivating new and exciting tools, including in nanoscience, medicine and in the fight against cancer.

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2. Zöttl, A. & Stark, H. Emergent behavior in active colloids. *J. Phys. Condens. Matter* **28,** (2016).
3. Hauert, S. & Bhatia, S. N. Mechanisms of cooperation in cancer nanomedicine: Towards systems nanotechnology. *Trends Biotechnol.* **32,** 448–455 (2014).
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Emergent Homeostasis: An Agent-Based Coupled Bone Remodelling and its Disruption

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Introduction

In healthy individuals, bone is constantly being broken down and reformed to ensure it can perform optimally according to the needs of the individual. This complex behaviour emerges from the cumulated actions of a limited number of cell-types acting according to their local environment.

We present an agent-based model of bone remodelling, incorporating the most significant factors that lead to this homeostasis. From this, we show how a collection of simple rules can lead to complex emergent behaviour in the biological domain, how systems such as this can be resilient to change within nominal limits and how further perturbation can lead to clinical conditions.

Background

Bone remodelling is principally driven at the cellular level by the activities of cells called Osteoclasts, which resorb bone, and Osteoblasts, which secrete new material. The delicate balance between these two types of cell emerges from a complex system of communicatory factors produced by a variety of actors within the bone marrow microenvironment. Perturbation of this balance can lead to clinical conditions such as osteoporosis. One condition which majorly disrupts this process is Multiple Myeloma, a incurable cancer that additionally causes Myeloma Bone Disease, leading to severely reduced quality of life.

Methodology

We use an agent-based modelling approach to simulate bone remodelling at the cellular level. This approach dictates that each cell within the system is simulated as a distinct entity. Each type of cell follows its own simple ruleset, aggregating towards balanced and coupled bone remodelling behaviour. Our approach simulates the most prominent actors within this system (osteoclasts, osteoblasts and osteocytes), their cellular lineages and the principal signalling factors that facilitate communication between these entities.

To guide the development of this model, we look first towards the CoSMoS methodology. This approach ensures that we capture our knowledge of the domain accurately and understand how to verify our results before performing experimentation on our model. To further ensure the veracity of our results, we are developing the model in stages to ensure confidence in each stage's feature-set before adding further complexity. This involves the development first of a healthy bone environment, followed by the perturbation of this to induce a clinical state, the introduction of multiple myeloma and finally the introduction of treatments for myeloma bone disease.

Future Development

We plan to continue development of our model to fully incorporate Multiple Myeloma. This will allow the effects of Myeloma Bone Disease to be examined at a cellular level and the reaction of the bone remodelling system to a number of contemporary, novel and proposed treatments for MBD to be observed. These observations will lead toward recommendation for future *in vivo* experimentation.

David Kirkham

Emergent learning affordancies of an out-of-class language learning modality

The Call for Papers defines emergence as 'system-level collective properties and behaviours that cannot be reduced to specific properties of their individual components'. Under this definition (or rather, in these terms), emergence may be seen as a relatively new preoccupation in the field(s) of linguistics. Chomsky's Universal Grammar (Chomsky 1957, 1965, 1995), its offshoots and responses, may be seen as addressing the emergence of child language. More recently, the term is used explicitly in Hopper's emergent grammar (Hopper 1987, 2011; Su 2016). In applied linguistics and language pedagogy, Larsen-Freeman (1997; Ellis & Larsen-Freeman 2009) situates emergence as a central concern within a complex dynamic systems view of language and language learning, a view that is echoed by the explicitly pedagogical work of van Lier (1996, 2004).

This talk will discuss two manifestations of emergent phenomena in an ongoing PhD project in adult second language pedagogies. Building on the work of Larsen-Freeman and van Lier (ibid.), socio-cultural learning theory in general (Lantolf 2000) as well as the researcher's own SCERT-framework (Kirkham 2017), the project investigates the affordances and appropriations of a particular, para-class learning environment (henceforth 'the modality') and how they complement the affordances and appropriations of alternative languages learning contexts (classrooms of various kinds; study abroad modalities; online learning approaches). The modality consists of a series of unstructured conversations between a group of learners and a dyad of native speakers/ expert users, each of which is followed by two structured reflective tasks. It is argued that this learning environment offers learning affordances not present (at least in the same way) in other pedagogies. For example, Kirkham (2018) discussed the discourse affordances and appropriations of the modality, contrasting them with alternative approaches to concerns around the pedagogical efficaciousness of classroom discourse (Hardman 2016; Heron 2018; Walsh 2006).

The two emergent properties to be discussed here are:

a) emergent awareness on the part of the learners of the degree to and manner in which they might plan for the conversations

b) emergent awareness on the part of the learners of their 'level' (i.e. interactional competence) in the context of the series of conversation

These learning- and learning identity-relevant properties are considered functions of the systemic nature of the modality and are therefore emergent under the above definition. Although the construct of 'planning for a task' and 'assessment of one's own language level' in the abstract may not unreasonably be considered part of the learners' conceptual equipment *ab initio*, the conceptual and behaviour specifics of these two areas emerge from sets of interactions of different kinds within the particular learning context of the modality.

Finally, the talk will discuss two proposed modifications for the second round of data collection (use of artefacts to mediate the discussion; deployment of a more directed reflection task) and speculate as to the effect of these on the above emergent properties.

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Quantifying emergent spatial patterns: an application in cancer

Janine Illian and Jim Bown

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Emergence can be exhibited through patterns in space, and we often recognise qualitatively such emergent patterns with relative ease. Indeed in some systems spatial phenomena are the first indicator of emergence. The quantitative description of spatial patterns is more challenging. Here, we consider cancer as a candidate emergent system. The processes that lead to cancer are multi-scale, with manifestations at genomic, proteomic, cell, organ and person scales. Central to cancer patient diagnosis and prognosis is the pathological assessment of the histopathological, architectural and morphological properties within patient tissue sections comprising hundreds of cells.

These tissue sections are typically a mix of cancerous and non-cancerous cells together with areas where there exists no tissue. Based on tissue section properties, pathologists stage tumours to estimate both cancer progression and patient outcome. Cancer staging predicts survival at the scale of the population well, but prediction is less accurate for individual patients. This is because the tissue is heterogeneous and pathological features are difficult to quantify. Image analysis can, in principle, provide quantitative measures of pathological features. To date, the focus has been on cell shape, the invasive edge of the tumour and proximity of the lymphatic system. Little consideration has been given to the spatial arrangement of cells.

Here, we present the findings of Jones-Todd et al (2018)†, which employs spatial statistics to quantify cancerous and non-cancerous cell distributions within tissue samples from colorectal cancer (CRC) patients. We used three different spatial point processes – void, Matérn and Thomas – to model the distribution of cells. We investigated the capability of each estimated point process parameter to discriminate between patient mortality outcomes. For mortality we found significant differences in the density of both cancerous and non-cancerous cells between patients who lived and patients who died.

†Jones-Todd, C. M., Caie, P., Illian, J. B., Stevenson, B. C., Savage, A., Harrison, D. J., & Bown, J. L. (2018). Identifying prognostic structural features in tissue sections of colon cancer patients using point pattern analysis. *Statistics in Medicine*. https://doi.org/10.1002/sim.8046

Rules for Metastatic Emergence

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We suggest that there is no fundamental difference between localisations of all kinds, from quantum quasi-particles to perceptions to living entities, and that all of these constitute metastates whose appearance obeys the same set of rules of emergence.

1. All observable structure is emergent. One major implication of this is that mathematics itself must be treated as an emergent structure. We must reconsider the relationship between information processing and mathematics; it is reasonable to consider mathematical structure to be a result of evolutionary processing, and not the mechanism by which it proceeds.

2. Any coherent structure is a metastate. There is no obvious fundamental distinction between the representations of elementary particles, of macroscopic entities, or even of the universe itself. This also implies the possibility of multiple relationships between the different levels of a hierarchical description, and between the various levels of descriptions of different entities.

3. A metastate **is** the entity. Consistently with Einstein's theories we should not attribute to reality an instantaneous universally-recognisable objective character. The only instantaneous reality we can correctly refer to is that pertaining to a local observer's context; it makes no sense to maintain that there is a "real" entity "hiding" behind the metastatic representation. An entity appears in its contextual world directly as its metastate, as a contextually stable approximate of its complete meaning.

4. A metastate's stability is contextually dependent. We can postulate a tendency towards emergence of a specific local approximative metastate, but the reality of its appearance and its observability will depend on the local conditions within which it must stabilise.

5. One and the same entity may appear as a number of different metastates. In a simple system these may be hierarchically sequential, but there is no obvious implicit requirement for rationally coherent relationships between different metastates. We could however anticipate a tendency towards hierarchical sequential relationships in a system exhibiting near-equilibrium in the relevant region of the phase space.

6. All the metastates of an entity are contextually real, and only contextually real. From one and the same viewpoint it makes no sense to describe a diamond as both a crystal and a collection of atoms, for example. It is unlikely that both of these representations will be simultaneously coherently approximates to the relevant regions of the universal phase space, and their mutual simultaneous identification would in all probability lead to logical inconsistencies or incompleteness (as found in extending classical quantum theory to large systems).

7. If the relevant contexts are simultaneously real, the metastates are also simultaneously real. It is difficult to argue against this, except by invoking an observer outside of the universal phase space, and therefore uncoupled from it and irrelevant. The implications, however, are enormous! This corresponds to the invocation in "normal" reality of a "multiple worlds" description of nature corresponding to the tentative propositions which have been made for quantum systems.

8. An observation consists of the interaction of a subjective metastate and an objective metastate. Whilst it may at first appear that these characters are both objectively defined, they only have meaning if we accept that both metastates can and will be simultaneously subjective and objective, and that both operate as observer and as observed, but that their interactions are unlikely to be reversible when summed over time.

9. Whilst unobserved individual metastates can be characterised as having a latent reality or capability for reality, it is the interaction of subjective and objective metastates which generates the property of reality in an observation. This is consistent with quantum theory, which describes only interactions at different instants of space-time, and not what occurs or exists between these instants.

10. Scale is a purely inter-metastatic phenomenon in that interactions depend on the metastates involved, and not on a structure which lies behind them. The apparent existence of strong effects of scale in nature itself therefore supports the view that the universe itself must equivalently be considered metastatic.

The role of Cell-level interactions in emergent behaviour in the fertilization process in pigs; a highly parallel Agent-Based Model using FlameGPU.

Morales-Garduno, C.[1]; Thurston, L.[2,3]; Walker, D.[1,4]; Fazeli, A[3,5]

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ABSTRACT

The complex process by which the spermatozoa reaches the site of fertilization in the female reproductive system is still not fully understood. It is known to involve a combination of chemical (chemotaxis), thermal (thermotaxis), and directional (rheotaxis) behavioural mechanisms affecting the spermatozoa-oviduct interaction. While the site of sperm deposition is highly species-dependent, the overall process is similar across mammalian species. After deposition, spermatozoa are in a non-capacitated i.e. they present limited movement and are not yet ready to fertilise the egg. After passing into the tube-like oviduct, connecting the ovary to the uterus, they will stay attached to the oviductal tissue awaiting a surface transformation process known as “capacitation”. Once capacitated, a spermatozoon presents alternating periods of more vigorous motility patterns i.e. progressive and non-progressive. Progressive movement allows the sperm to advance forward faster, whereas non-progressive movement resembles random movement. This combination of movement seems to be essential for a successful outcome. Hence arrival at the site of fertilisation is an emergent outcome of the interactions of individual sperm with the complex oviductal environment.

Although its overall shape is species dependent, a common feature across species is the inner topological characteristics of the oviduct. The internal tissue (resembling a tightly folded cloth) presents many cave-, valley-, and pit-like formations. All this complexity adds up creating a navigational challenge for spermatozoa.

To understand how this complexity affects the fertilisation process, we applied an Agent-Based modelling approach. We defined each individual spermatozoon as an autonomous agent bound to simple rules i.e. forward motion, change of direction, collision with the oviduct walls. However, assumptions about how frequently those changes occur, their magnitudes or direction are not encoded in the system. Instead, these are provided per simulation in the form of probabilities per time step and in user-specified parameters obtained from biological literature. Non-deterministic system-level biological behaviour, including the spermatozoa distribution at key regions of the oviduct, the time required to achieve fertilisation, then emerge due to the individual-interactions of each spermatozoon with the oviduct walls.

Our model, implemented in FlameGPU, an Agent-Based Modelling framework targeting highly parallel processor available in Graphics Processing Units, was previously validated to generate biologically grounded results for the mouse gametes and oviduct. More recently, the model was extended to support investigation using porcine-derived parameters and oviduct structure and we are now using the model for exploring the relationship between low spermatozoa motility parameters and diminished fertility in pigs. Such a link has been reported to exist in humans due to exposure to specific pollutant agents, or due to dietary choices, or due to Sexually Transmitted Diseases. Future work will look to expand our model into a multi-scale model to further explore the interlink between the cell-to-cell communication mediated by nanosized vesicles and the emergent outcome of the fertilization process.

In summary, we have applied an agent-based approach in order to uncover the traits underpinning the system-level behaviour in the fertilisation process that cannot be understood by simply extrapolating the properties of a few spermatozoa agents.

Emergent clustering of species traits as a driver of biodiversity

Rebecca Mancy
University of Glasgow

I will present work based on simulated communities of phytoplankton which demonstrates that, in the context of fluctuating resource constraints, biodiversity is maintained through an emergent pattern in which the traits of coexisting species form clusters. Using a well-established resource-competition model, my colleagues and I showed that a complex dynamic pattern in the available ambient resources arose very early in the self-organisation process and promoted the growth of species whose traits fell within one of a small number of clusters. These findings are consistent with the idea that biodiversity is maintained through 'lumpy coexistence' [Scheffer M, van Nes EH (2006) *Proc Natl Acad Sci USA* 103:6230–6235]. I will expand on the original work by exploring several approaches that might be used to quantify the emergence of patterns of biodiversity. To do this, I will apply both established measures of biodiversity, and novel approaches based on Rényi entropy that have been developed by my colleagues at the University of Glasgow. I will discuss what these measures might reveal about emergence, and raise more general issues relating to the quantification of emergence and self-organisation.

The note you play…

Yasmin Merali, University of Hull

ABSTRACT

Atul Gavandi said (2014 Reith Lecture): this is the century of systems. His point was that 20th Century scientists were occupied with establishing the fine-grained structure of constituents of life and the universe, and the challenge for the 21st century is to understand how these interact to deliver whole systems *behaviours*.

The vagaries of complex socio-economic systems have long been a source of consternation to many of us. Recent examples include the 2008 financial crisis, Brexit, ISIS, and the institution of Donald Trump as President. Less sensational but of critical importance in the UK are the state of the national health service, provision for the elderly and infirm, the educational system, the rise of radicalisation and violent extremism.

The title of this talk is taken from Miles Davis: "... it isn't that the note you played is right or wrong, it is the one you play next that makes it so..." Socio-economic systems are complex adaptive systems, embodying path dependency and emergent behaviour. Viable systems will find the note that works, and the next and the next…

Policy makers in the networked world are confronted with systemic phenomena that they cannot ignore. In this talk I explore the extent to which even a rudimentary understanding of the dynamics of emergence would change the tune they play.

BIOGRAPHY

Yasmin Merali is Director of the Centre for Systems Studies and Professor of Systems Thinking in the Faculty of Business Law and Politics at the University of Hull. Her personal research transcends traditional boundaries between the *natural*, *human* and *information* sciences by drawing on complex systems science to study socio-economic systems at all scales and across diverse domains in the network economy. She is an Expert Evaluator for the EU, and has served as an elected member of the Executive Committees of the *Council of the European Complex Systems Society* and the *UNESCO UniTwin for Complex Systems Science*. Before joining Hull she was Co-director of the Doctoral Training Centre for Complexity Science at the University of Warwick. She has extensive consultancy experience in public, private, and third sector organizations and received two BT Fellowships and an IBM Award for her work on knowledge and complexity. She is the author of several reports for government and industry, and her most recent journal articles appear in *MIS Quarterly*, *Organization Studies*, *Journal of Information Technology*, *Journal of Strategic Information Systems*, the *International Journal of Operations and Production Management,* the *International Journal of Forecasting* and *Phys. Rev. E.*

How structured outputs help us see emergent properties of social and political knowledge systems

Author: John Forrester, YCCSA (acknowledging the contributions of Richard Taylor, SEI; Lydia Pedoth, EURAC; and David Zeitlyn and Howard Noble, Oxford)

Abstract

Environmental governance is fraught, and various forms of science communication are appealed to as solutions to that fraught issue. This paper makes the point that participatory methods with highly structured outputs are particularly appropriate to be used to better understand complex human-environmental systems. This paper describes how some established and novel methods co-constructing structured outputs (participatory agent-based modelling; co-constructing computer games; participatory GIS mapping; Q-methodology; and participatory social network mapping), can be used to engage stakeholders in iterative, constructivist communication.

Importantly, it also looks at some of the necessary social theory underpinning such approaches such as Zeitlyn's 'merological anthropology'. It also considers how such methods allow social researchers and stakeholders to co-create a structured 'reality' separate from the reality it represents. Critically, such representations are 'partial'. Yet our findings show that when applied to a range of important social issues (e.g. development and disaster risk management) such methods provide communication opportunities and spaces for reflection and constructivist learning. The structured outputs allow stakeholders to 'mirror' their human-environmental system to collaboratively think about gaps and problems, and emergent properties of the systems such as unintended consequences.

Keywords: environment, climate change, risk, participation, emergence

Climate Change: A Catalyst for Human Emergence
(Systems Thinking to Save the World)

Kerry Turner, Centre for Systems Studies, University of Hull

'Climate change' is two words: 'climate' and 'change'. In this paper I propose that the climate is changing but humanity fundamentally is not, and I explore why this is. I present three causal loop diagrams: one on the powerful hydrological feedback loops driving the Earth's temperature system; one on the system controlling human temperature; and one on the system driving human behaviour when faced with potential future danger. Then I explore their similarities, linkages and implications.

The Earth model builds on work done by Dennis Sherwood (1) and incorporates new thinking by Walter Jehne (2) The human behaviour model emerged from a Systems analysis of the Grenfell Tower fire disaster (3).

I examine the consequences of proposed interventions such as targets for emissions reduction. This reveals that, whilst reducing emissions is a good thing to do, it is insufficient to avoid major consequences for humankind. Systemic interventions to draw down legacy carbon by regenerating the soil carbon sponge (Jehne) are also considered, as is human population management. The implications for action on these leverage points are presented as four future scenarios.

The paper argues the need for a well calibrated System Dynamics model capable of assessing the full potential for regeneration and answering key questions such as "what is the carrying capacity of the Earth given a fully operational carbon/water cycle?" However, this must be accompanied by efforts to overcome the inertia in human behaviour change. In this, reaching children (as the key stakeholders of the future) with clear systemic insight and thinking tools is the longer term system fix.

Systems thinking tells us we must consider the whole, yet we systems thinkers have persisted in optimising the parts. *Ultimately, in terms of the planetary system, there is only one whole*. All other things are parts of that whole. They are subsystems. Climate change reminds us of this basic truth. We can save humanity (and ourselves) from major impacts with the small yet hugely significant decisions we take each day of our lives, and how we treat the land in our care. In those decisions lies the chance for us to emerge as truly systemic beings with a strong and reverent connection to the single system we are all a part of.

References

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(2) http://www.globalcoolingearth.org/wp-content/uploads/2017/09/Regenerate-Earth-Paper-Walter-Jehne.pdf
(3) Paper presented at OR60 in September 2018 https://youtu.be/Fkivqq-NU_I

Emergence and Topological Order in Classical and Quantum Systems

Tom McLeish, Tom Lancaster and Mark Pexton

There has been growing interest in systems in condensed matter physics as a potential source of examples of both epistemic and ontological emergence. One of these case studies is the fractional quantum Hall state (FQHS). In the FQHS a system of electrons displays a type of holism due to a pattern of long-range quantum entanglement that some argue is emergent. Indeed, in general, quantum entanglement is sometimes cited as the best candidate for one form of ontological emergence. In this paper we argue that there are significant formal and physical parallels between the quantum FQHS and classical polymer systems. Both types of system cannot be explained simply by considering an aggregation of local microphysical properties alone, since important features of each are globally determined by topological features. As such, we argue that if the FQHS is a case of ontological emergence then it is not due to the quantum nature of the system and classical polymer systems are ontologically emergent as well.

Emergent properties of bio-inspired hardware

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State-of-the-art electronic design allows the integration of complex electronic systems comprising thousands of high-level functions on a single chip. This has become possible and feasible because of the combination of semiconductor technology providing atomic-scale devices, allowing very large scale of integration (VLSI) of billions of transistors, and electronic design automation (EDA) tools that can handle their useful application and integration by following a strictly hierarchical design methodology breaking down a system into blocks, sub-blocks or cells. This results in many layers of abstraction within a system that makes it implementable and verifiable, hence, explainable which is usually desired. However, while many layers of abstraction maximise the likelihood of a system to function correctly (because it can be verified and debugged) this can prevent a design from making full use of the capabilities of a process technology.

Moreover this places electronic systems, in the way they are currently designed, at opposite ends of the scale from emergence as—by design—they can be understood from a purely reductionist point of view. The fundamental component of an electronic system, the transistor, is known and the design hierarchy is constructed bottom-up. Starting at the top level, this hierarchy can be traversed in the opposite direction and each block can be understood and explained by looking at the components it is made of. The whole methodology has been developed to avoid unforeseen behaviours and therefore there appears to be no room for emergence.

However, the ever-increasing transistor density and design complexity makes modern systems brittle. As we start to meet fundamental device scaling limits when touching the atomic scale, design challenges arise including the thermal/power constrained Dark Silicon and other deep sub-micron silicon fabrication issues such as intrinsic variability and electrical wear out (ageing). This gives VLSI designers a large number of pessimistic design constraints that must be met to avoid faults and guarantee a certain lifetime of a device. Despite that, the yield (percentage of chips on a silicon wafer that operate according to specification) continues to decline.

This gives rise to the idea of biologically-inspired hardware, which is indeed capable of emergent behaviours or features. Of course the challenge here is to adopt and implement these concepts while achieving a "next-generation" kind of electronic system which is considered at least as useful and trustworthy as its "classical" counterpart—plus additional features. Considering this, the question may be asked whether it is acceptable or useful to speak of emergence at all in the context of bio-inspired hardware, given that the bio-inspired parts also need to be designed using a VLSI methodology and must be comprehensible.

The concept of "emergence" is usually taken to relate to something like an unexplained or unexplainable appearance of an entity or property which is not further reducible to known interactions of other components (non-reductionist, holistic) [1]. Although this is quite vague and short of a definition, a variety of phenomena, including biological dynamics, chemical interactions and various mental phenomena, are labelled as "emergent". Accordingly, a wide range of definitions of "emergence" can be found in the literature and are, thus, generally, almost useless. For example, it is not useful to conceive of emergence in terms of "unpredictable" when trying to model the behaviour of an ant colony.

A useful definition of "emergence" when thinking in terms of engineering and computer science is found in [2], [3]. There, any property or entity within a particular *context* is called "emergent", if it is a property or entity which cannot be further explained in that *context*. A distinction is made between a "strong" concept of emergence, which implies an inability to reduce explanations to simpler concepts, and "weak" emergence, which implies that complex systems posses properties which are not possessed by their parts, but that those properties are explicable in terms of those parts. Hence, when an (electronic) system, comprised of a set (hierarchy) of interacting entities, gives rise to properties which cannot be analysed into components within some context, then for the purpose of that particular causal relationship and that particular context, that system is a singular, irreducible entity, and those properties are emergent. For example, when observing ants by looking at the behaviour of the entire colony rather than the individuals, the colony can indeed be regarded as a singular entity.

Based on this discussion and definition of "emergence", it can now be suggested that drawing inspiration from structure and behaviour of biological systems can bring new, useful behaviours to electronic systems which are explainable and verifiable at some lower level, but which can indeed be regarded as "emergent" properties, e.g. in the context of the entire system.

In this case, the emergent property sought to establish is system-level fault tolerance, the inspiration from biology are social insects (ant colonies), and the hardware system is a many-core computing architecture where application tasks and data need to be allocated transferred and organised. The model of processing elements communicating amongst each other via a network on chip (NoC) provides a conceptual link with many scalable biological models.

Based on this, a self-optimising and adaptive, yet fundamentally scalable, design approach for many-core systems based on the emergent behaviours of social-insect colonies are developed. Experiments aim to capture the relevant decision processes made by each member of the colony to exhibit such high-level behaviours and embed these decision engines within the routers of the many-core system. Results with the bespoke 128-core Centurion platform suggest that there is potential for the social insect model as a distributed, embedded intelligence within a many-core system and with the relevant knobs and monitors, such as clock frequency and temperature, to close the loop for emergent autonomous adaptation and fault tolerance [4], [5].

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Emergence in a Replicator-Parasite Automata System (R-PAS)

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How can a system of simple RNA-like replicators increase its complexity through evolution? Artificial Replicator-Parasite (R-P) systems explore the dynamics of evolution in such systems [1]. If variability in replication is allowed, parasitic entities tend to emerge which threaten to drown the replicating system. These systems have three reaction classes where R is a replicator, and P is a parasite. There are three reactions: $R : R$ which produces a new R, $R : P$ which produces a new P; and $P : P$ in which no new entities are produced.

When the rates of these reactions are allowed to evolve, the system will diminish to extinction in a well mixed situation (e.g. as implemented in ordinary differential equations), but can survive in spatial explicit systems such as 2D CA where the entities exist in cells arranged on a toroidal grid. This survival is due to the emergence of spatial patterns.

Parallel to this research, work on Automata Chemistries has also documented the emergence of parasites in replicator systems [2]. Here the replication function is encoded explicitly via a sequence of computational operators including the act of binding, the rate of which is controlled by sequence alignment between the partners. This binding system is sufficiently sophisticated to allow an R-P like model to be implemented - thus it is an R-PAS (a Replicator-Parasite Automata System). The stages of replication are encoded in the sequence and can be affected by evolution. The key advantage of this approach is that the mechanics of replication can be reconstituted through evolution and allow different functions to emerge. This leads us to ask: how does this recomposition affect the replication dynamics? Do new behaviours emerge? Is there any increase in complexity?

To explore these questions, we extended the Stringmol Automata Chemistry to run on a toroidal grid, with reactions permitted only in the Moore neighborhood of each entity. We ran 25 trials to 2 million timesteps, using five different configurations to counter effects of arena shape and initialisation. Eleven of the Twenty-Five systems went extinct before 100,000 timesteps, indicating that the parasites overwhelmed the system before the spatial patterns became established. Only three of the systems that passed this point went extinct.

The following trends were observed in all of the systems that ran to 2 million timesteps: Folowing the initilisation with the seed replicator, parasites emerge quickly, and are replicated faster than the replicators themselves because they are shorter, but the system survives due to the emergence of wave-level selection, as shown in figure 1, left. Selection for replication rate leads to shortening of the sequences, but then several mechanisms for resistance to parasites emerge, e.g. slow replication of any entity, reducing the advantage parasites have by being small. Through this complex reaction systems emerge (figure 1, right), which can take several forms:

1. *Binding wars (hypercycles)*- in whch an $R_x : R_y$ recation produces a new R_x or R_y, and parasites can only exploit one of the partners.
2. *Rate wars* replicators emerge with slower rates of replication to reduce the advantage of being shorter. This permits capacity in the replicator sequence to evolve new behaviours
3. *Diversity wars* risking the error catastrophe, some replicators are pathologically diverse, with long chains of short repeats in the sequence.
4. *Rule exploitation* although no movement is allowed in these systems, some reactions emerge where one of the parents destroys itself. This has the effect of creating a sparse distribution of replicators which is more difficult for the parasites to exploit, but at the risk of individual replicators becoming isolated and unable to reproduce.

The key result of these experiements is that despite the primary selection pressure to efficient replication, and therewith decrease in the size of the replicators, the individual replicators develop a range of strategies to exploit the capabilities and vulnerabilities of others in the system. In this way new levels of complexity arise.

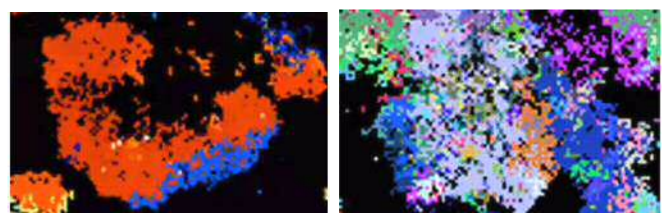

Figure 1: phase transitions in an evolving R-PAS. R-P wavepatterns (left) and diversity wars (right)

Conclusion The R-P CA models are a good description of the early phases of evolution of the AChem, where changes in mean population levels reflect the rate parameters of these models as parasites emerge.

As expected, the systems do not survive unless spatial patterns, and higher levels of selection emerge soon enough to avoid extinction. If they do survive the initial phase trends emerge towards higher population, higher diversity and increasing complexity, with associated reduction in the chance of extinction. These phenomena present an exciting result, offering new insight into the transition from selection for speed of replication to selection for a *range* of emergent, complex behaviours.

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Strong Emergence and Creative Systems

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Most work on the problem of emergence is directed at self-organising systems and focusses on the process by which an organized structure or pattern emerges from the collective dynamics of the individual objects making up the system. While these emergent structures may have certain functionalities, e.g. increased heat transport, they are essentially just patterns in the collection of their constituent particles or objects. Unlike their constituent objects, they have no existence as independent entities, and they cannot, simply as patterns, act on their environment—in other words, they have no agency. For this reason the emergence of self-organized systems is referred to as *soft* or *weak emergence*.

Strong emergence, on the other hand, refers to the appearance of new objects, or new types of objects, in a system. We identify three levels of strong emergence, but focus on the last two:

1. In physical systems: In high energy physics, forces and particles emerge through symmetry breaking.
2. In chemical systems: In chemical reactions, new molecules can emerge through a combination of existing molecules or atoms; the combinatorial space of chemistry provides a vast array of possibilities for new compounds to emerge with different, potentially novel characteristics.
3. In living systems: Emergence is initiated and guided by endogenous models of the system and its relationship with its environment; we include in this category the meta-systems of life such as ecological, social, political, technological, and economic systems.

At relatively moderate energy levels, physical systems produce an increasing variety of chemical compounds. These molecules have an independent existence and distinctive properties, like a characteristic colour or solubility in water, that are not simply the sum of the characteristics of their constituent atoms. They also have a kind of passive agency: for example, they can interact with each other chemically to produce new molecules with new properties, like a new colour. Of course they can also interact physically, by means of collisions, to produce weak emergence, for example in the form of a convection cell or a cyclonic storm. Chemical reactions can also result in the simultaneous occurrence of both strong and weak emergence, as when reacting molecules and their products generate the macroscopic self-organized spiral patterns of the Belosov-Zhabotinsky reaction.

While self-organized systems are forced to a state of lower entropy by an exogenously determined flux of energy, living systems create and maintain their organized structures in order to proactively import energy and thus maintain a state of lower entropy. These systems are thus characterised by agency: they act to maintain themselves. This causal circularity is a characteristic of living systems, and is a function of their containing models of themselves and their environment (e.g. encoded in DNA, or in ideas): the models guide the creation and functioning of the system of which they are a part—i.e. they provide context dependent rules of behaviour that supplement the laws of physics and chemistry. A model that is a part of a living system can function as a model only by virtue of its semantic content, since in order to be a model it must represent another system, a system of which, in the case of living organisms, it is itself usually a part. The modelled system thus provides the model with its semantic content. Semantics may be the most fundamental emergent property of living systems. This conclusion conflicts with the reductionist position that scientific explanation can ultimately be purely formal and syntactical.

The models that guide the generation and behaviour of living systems are necessarily self-referential, since they are models of a system of which they are a part. This means that they cannot be represented purely as mathematical structures. Instead, the mathematical structures must be embedded in executable algorithms which are able to model their own behaviour and alter themselves on the basis of their models of themselves. Thus only computational modelling can hope to capture the essence of emergent phenomena as they are manifested in living systems.

Complex Thinking and Emergence

Ana Teixeira de Melo and Leo Caves

The advent of Complexity, as a scientific field focused on the study of complex systems, has highlighted some of the most fascinating features of nature, and of both the biological and social worlds. The concept of emergence appears as one of the most intriguing ideas and likely one of the less well understood (Corning, 2002; Goldstein, 1999). It encapsulates the creative power of the universe and its biggest mysteries and point towards a relational matrix sustaining it. It reveals the processes that connect every entity of the universe with every other, suggesting a relational organisation that underlies all processes of becoming and transformation (Whitehead,1979).
Different modes of thinking afford different possibilities of discovery/construction of the world and different possibilities of action (James, 1907). Throughout its history, humanity has experimented with different modes of coupling with the world and of creating knowledge through that relation (Baggini, 2018). Modern science has crystallised a few modes placing itself in a position of blindness in relation to the complexity of the world (Morin, 1990). Complexity Science represents a call for the transformation of our modes of thinking which need to be capable of making sense and develop tools for the investigation of critical features such as emergence (Morin, 1992; Waddington, 1977).
Building upon Morin's contributions (Morin, 1992), we propose a notion of complex thinking as a mode of coupling with the world (Varela, Thompsom, & Rosch, 1991) that not only attends to key properties and processes such as those associated with emergence but also enacts them supporting emergence in the process of thinking. Complex thinking appears as an element of coupling between the world and its observers and a critical process associated with their co-emergence and co-evolution. Through attending to complex processes and properties of the world, complex thinking guides the mapping of its complexity in ways that could also fit under the label of complexity thinking. However, by enacting complexity, complex thinking appears as a distinct mode of thinking that allows for an indirect production of knowledge through processes of emergence that are sustained in a close and special type of coupling (that enacts properties of complex systems) with a target system. It is closer to a type of abductive thinking (Peirce in Fann, 1970) associated with imaginative leaps (Whitehead, 1979) that generate relevant information (as differences that make a difference- Bateson, 1979) about a target system, in the form of new insights and hypotheses (Reichertz, 2014) that informing new actions and modes of relating to that system, illuminate particular aspects not fully understood from the onset of the coupling and pave way for other ways of exploration. This notion of complex thinking, framed by a relational ontology and epistemology, is a critical coupling element of the co-emergence of the world and its observers as entities capable of drawing distinctions (Goguen & Varela, 1979), of knowing in multiple ways and generating perturbations and differences through their coupled actions, that contribute to processes of differentiation of integration implicated in emergence.
In this presentation, we will explore a notion of complex thinking that relates to the notion of emergence (Caves & Melo, 2018), and explore the heuristic value of the concept in supporting disciplinary and interdisciplinary studies where both the process (of emergence) and the (emergent) outcome are explored recursively.