UNPREDICTABLY PREDICTABLE

A COMPLEXITY THEORETIC DEFINITION OF EMERGENCE

Simulation of Adaptive Behaviour - EASY MSc
Department of Informatics - University of Sussex – Brighton - United Kingdom

---

Abstract

Emergence versus reduction is one of the oldest debates in philosophical history; yet it has been only recently, with the rise in computer power, that science has been able to make any study of emergence at all. This paper aims to briefly review the current work in defining this formidable concept and attempts to introduce a more formal definition in terms of complexity theory and predictability.

---

11 INTRODUCTION

The emergence reduction debate began in around 350BC with the opposing schools of Aristotle and Democritus. The Aristotelian philosophers (most notably Plato) objected vehemently to the mechanistic purposelessness of atomism saying that it could never produce the beauty and form of the world; in the words of Plato we ask, "*is the world created or uncreated*?". This position was, however, most eloquently stated by Aristotle within the treatise entitled *Metaphysics*; he proposed an emergentist alternative to the philosophy of the atomists stating that "*the whole is greater than the sum of its parts*".

Despite the continued philosophical debate, science, is seems, neglected this alternative notion, driven instead by the progressive powers of chemistry and physics (the two towers of the reductionist dogma). As science advanced, it increasingly began to restate the whole in the reduced terms of its multifarious parts; water and earth was broken into atoms and fire and wind identified to be thermodynamic forces blindly following Newtonian laws. With mechanism came predictability and with predictability came the capacity to harness these great forces of nature. Industry and technology feasted on the knowledge brought forth by the sciences of reductionism and the more we broke the world apart the more we seemed to understand it.

However, over the last century this paradigm has begun to shift (Capra 1996; Davies 2003). During the 1920s physicists delving the furthest depths of the atomic world were dragged away from the simple realm of Newtonian mechanics. The quantum world they were exploring was a place of probability and unpredictability; crumbling apart the very ground upon which the fundamental atomists once stood (Schrödinger 1926).

Within biology too, scientists unsatisfied with the reductionistic answer to the question of life began to look at a more holistic explanation; defining living organisms in terms of autopoietic systems and cognition in terms of information processing and self-maintenance (Maturana & Varella 1980).

A new ontology was forming; in which the world was viewed not in terms of atoms and laws, but in terms of nested systems; and to study it, scientists began to construct a new kind of science (Wolfram 1984).

Aided by the exponential growth of computer power, scientists began to develop a general theory of these nested systems (Van Bertalanffy 1969); examining their nonlinear dynamics (Lorenz 1963; Feigenbaum 1978), their natural self-organisation (Prigogine 1981; Kauffmann 1993; Lovelock 1979) and their apparent hyper-structures and hierarchy (Mandelbrot 1977; Kauffman 1993; Baas 1994; Morowitz 2002).

Known now as the study of complex systems, this burgeoning field is slowly turning the reductionist worldview on its head. Rather than trying to describe wholes as collections of parts, we are now examining collections of parts and finding strange and unpredictable new wholes. We are, at long last, beginning the scientific investigation of emergence.

This paper aims to briefly review the current work in defining this concept and will attempt to introduce a new definition in terms of complexity theory and predictability. We do, however, heed the warnings of John Holland, in his exhortative book on the subject; "*despite its ubiquity and importance, emergence is an enigmatic, recondite topic, more wondered at than analysed … it is unlikely that a topic so complicated will submit weakly to concise definition*" (Holland 1998).

12 FOLK DEFINITIONS

In attempting a formal definition of such a difficult subject, it is useful to begin with a more general folk understanding of it first.

The most widely considered, and intuitively understood, such notion is Aristotle's original observation that the whole (lets call this X) is greater than the sum of its parts (lets call these Ys). In this folk definition, Xs are '*more than just Ys*' or '*something over and above Ys*' (van Gulick 2001).

Most researchers appear to share this general and simplistic notion of emergence; and James Crutchfield (1994) expands upon it slightly by saying that "*over time, 'something new' appears at scales not directly specified by the equations of motion"*. He notes, however, that, for this definition to be useful, *"one must specify what the 'something' is and how it is 'new'"*.

And herein lies the problem; there is currently no agreement or even debate regarding what the '*something'* is or how it is '*new*'.

For some, the distinction between the two is ambiguous and Van Gulick (2001) makes a concerted effort to provide clarity by driving a philosophical wedge between the metaphysical emergence of properties (the something) and the epistemological emergence of cognitive explanation (the newness). However, this distinction only seems relevant to *thermodynamic emergence* (Cariani 1990), and ignores the emergence of formal structures or intrinsic computation (Crutchfield 1994). Further still, it is unclear upon which side of the ontological boundary we should place some of the more observationally dependant, or subjective examples of emergence such as colour or temperature.

Such subjectivity in emergent phenomena is a key issue for many who attempt to define the *something,* and is commonly known as the '*problem of interpretation*' (Forrest 1990). Crutchfield (1994) shows great concern regarding the extent to which pattern and structure may lie purely in the eye of the beholder; "*it is the observer or analyst who lends the teleological self to processes which otherwise simply organise according to underlying dynamical constraint",* and importantly if that observer lacks the analytical know-how then, "*the obvious consequence is that 'structure' goes unseen due to the observer's biases*". To tackle the issue he puts forth the proposition of *intrinsic emergence*; briefly described as the capacity for a system to be able to capitalize on the emergent patterns that appear. There is no external referrer (observer) and the emergent pattern lends additional functionality to the underlying system itself.

In a similar vain, many other authors attempt to redefine emergence in terms of the functional enhancement that the 'something' brings to the system as a whole. For example Forrest's notion of computational emergence redefines emergence in terms of the enhancement of computational capacity (Forrest 1990); and more generally, in complex biological systems such as bee foraging, emergence is often used to describe the process by which new scales of adaptive behaviour arise (Seeley 1991). Holland (1998), however, helps to smooth these ambiguities a little by highlighting that "*the context in which persistent emergent pattern is embedded determines its function*".

For others, the emphasis of emergence should be more heavily placed on the 'new' than on the 'something'. In particular, Capra (2002) defines emergence as "*the creation of novelty*", a view which appears to be based, at least in part, on Cariani's work on *combinatorial* versus *creative emergence* (Cariani 1990; 1997). For Cariani, "*emergence concerns the means by which novelty arises in the world*"; a viewpoint which slants ones perspective towards the philosophy of creativity, and is in contrast to the more general view of emergence as "Xs being something over and above Ys". As such, although interesting and with a degree of overlap, it is felt that much of Cariani's work falls outside the field (Kubik 2003).

For others the emphasis of the 'new' is slightly less extreme. Van Gulick (2001), within his definition of epistemological emergence, distinguishes two distinct kinds of novelty which he calls *representational emergence* and *predictive emergence*. The former states that the laws and framework of the parts cannot adequately *describe* the emergent phenomena. The latter states that the laws and framework of the parts cannot adequately *predict* the existence of the emergent phenomena.

This view of predictive novelty is also highlighted by Baas (1997) with his definitions of *deducible emergence* and non-deducible (*observational*) emergence – wherein an emergent property is deducible if it can be deduced (predicted) using the theory, structures, interactions and observations of the parts.

So too for Ronald, Sipper and Capacarrerre (2003) who state "*emergence consists in the fact that we cannot describe (predict, expect) the behaviour of the whole system from the description of its individual parts*".

Finally, for some, the notion of the 'something' and the 'new' is simply inadequate. Kubik (2003) charges all of the current work in the field as being either too broad or too strict; as being too informal and too intuitive; as being overly philosophical; and as lacking an adequate modelling technique and unified framework. His desire is to build a formal "Theory of Emergence", citing John Holland as his guide, and he wishes to base it on multi-agent systems and the mathematics of grammar based systems. These sentiments are partly shared within this paper, but from the alternative perspective of complexity theory.

Figure 1: Gershenson's Classification of Discrete Dynamical Systems

Complexity theory is the branch of dynamical systems theory which concentrates its study on the "*interesting"* class of behaviours found within discrete dynamical networks (DDNs) (Wolfram 1984; Langton 1989). The field is growing steadily within a wealth of observable DDNs; each with their own set of interesting behaviours lying somewhere on the overlap of order and chaos - see figure 1 for Gershenson's (2004) classification of DDN space.

The most widely studied and publicised class is undoubtedly that found by Stanislaw Ulam and John von Neumann in the 1940s; the prodigious Cellular Automata (CA).

A CA can be defined as a ***D***-dimensional lattice with a finite state automaton placed at each site in the lattice. Each automaton has ***Q*** distinct states and at any given time (***t***) an automaton can be said to be in the specific state. Each automaton calculates its next state from a lookup table of rules based on the configuration of its local neighbourhood. The automaton rule table would simply consist of a rule for each and every possible configuration within the *N* neighbourhood template. Numerically speaking, therefore, a particular class of CA has $|Q|^{|N|}$ possible rulesets.

The most famous of these is John Conway's Game of Life (commonly referred to as ruleset 23/3). Based on von Neumann's 2-state, 9-neighbour checkerboard CA, the Game of Life contains a wondrous array of interesting global behaviours; including, pertinently, a number of phenomena which are commonly considered to be prime examples of emergence. Of these, the predominant pattern for study is, undoubtedly, the simple and meritorious glider.

The glider contains and signifies everything which complexity theory aims to study; and for us to clearly understand the extent to which it is so compelling, we must compare it to the more common sets of behaviours possible in a complex system; the opposing forces order and chaos.

First, however, a brief review of order and chaos with respect to predictability and the mathematics of information theory. Following Gregory Chaitin's (1974) lead, let us consider the following series of binary digits:-

(a) 01010101010101010101
(b) 01101100110111100010

Chaitin promotes (a) as a *non-random* series due to its informational compressibility (it can be reduced to a minimal program which simply prints 01 over and over again). As such, this series it also said to be predictable (we are able to use the compression to accurately predict the next digits to be 0 and 1).

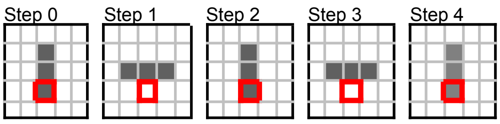
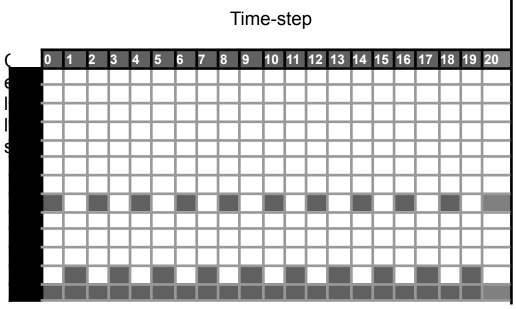


Figure 3a: The whole of an ordered CA



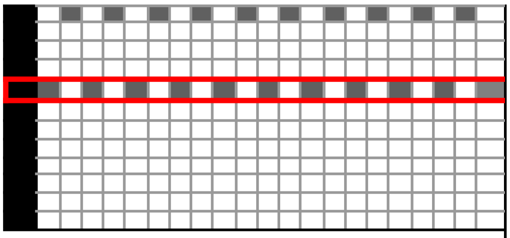


Figure 3b: The parts of an ordered CA

The second series (b) is said to be *random* because it is not compressible (it cannot be reduced to a minimal program). It is equally said to be unpredictable as there is no method (other than by sheer guesswork and chance) by which you can accurately predict what the next digits will be.

Such work concentrates on the randomness of a sequence, or, to put it into context, on a system with just *one* variable changing over time (a non-complex dynamical system if you will).

However, more recent studies of *complex* (many variabled) dynamical systems have shown a very similar bisection can also be made. Ordered systems are those whose global behaviour is predictable and chaotic systems are those whose behaviour is unpredictable.

To bring these two kindred ideas together, consider the cross reference outlined below entitled predictability in dynamical systems (figure 2).

With reference to this position, one may now return to the hearth of complexity theory in an attempt to establish what is unique about the glider and what relevance all this has on a definition of emergence.

First, a study of a complex system which displays ordered behaviour. The ruleset determining this behaviour is the 23/3 Game of Life ruleset.

Figure 3a illustrates how the state of the CA changes over time; this is the behaviour of the "whole". It is intuitively clear that the system is predictable from this perspective; it repeatedly

Figure 2: Predictability in dynamical systems

Figure 3b illustrates the same information over a longer number of time-steps but this time it allows each cell (part of the system) to be considered separately. As can again be clearly seen every part can be expressed in terms of a non-random sequence. The highlighted cell 18, for example, follows the converse of the non-random sequence previously examined and said by Chaitin to be compressible (101010101010… etc).

So, from the perspective of the whole we have a predictable/ordered system, and from the perspective of its parts we have a collection of predictable/non-random sequences.

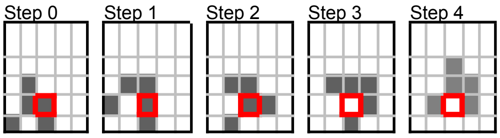


Figure 5a: The whole of a glider

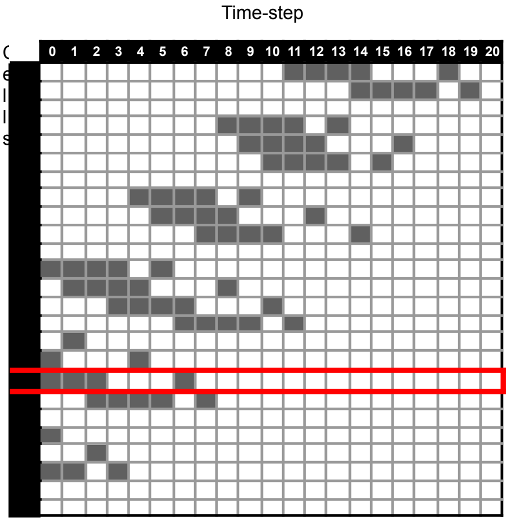


Figure 5b: The parts of a glider

An important note at this point is that we are in this second example considering each cell in *isolation*; free from its neighbouring cells and free from the underlying mechanics driving its behaviour. Such a measure allows us to clearly consider “the sum of the behaviour of the parts” which, according to Kubik (2003) is a crucial and overlooked aspect to any formal definition of emergence.

Lets us now compare the above with an example of chaotic behaviour. The ruleset determining this behaviour was the arbitrarily chosen 467/24 rule.

As before Figure 4a illustrates how the state of the whole CA changes over time. It is intuitively clear that the system is unpredictably chaotic from this perspective. No obvious pattern of behaviour exists and the general behaviour depends entirely on the initial conditions of the system.

Figure 4b illustrates the same system but in the terms of its constituent parts. Examining the behaviour of cell 18 highlights a random sequence very similar to that examined earlier (i.e. 10101010011101… etc).

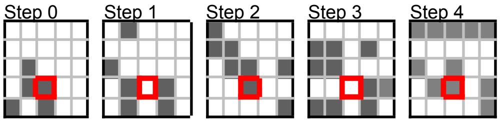


Figure 4a: The whole of a chaotic CA

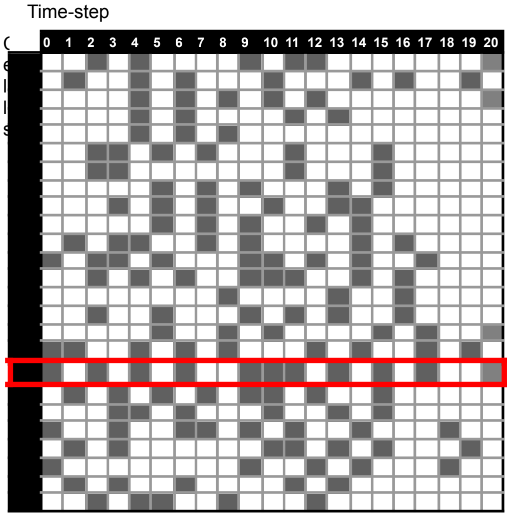


Figure 4b: The parts of a chaotic CA

So, from the perspective of the whole we have an unpredictable/chaotic system and from the perspective of the parts we have a collection of unpredictable/random sequences.

And so finally, let us now take a look at our glider. Figure 5a illustrates the behaviour from the perspective of the whole and shows a simple period-four cycle with a diagonal translation. Like our first study, this behaviour is predictable; one is able to accurately and precisely state the exact future of the whole system. As such, one may choose to call this behaviour (from the perspective of the whole) ordered.

However, in examining the behaviour of the individual parts, we are not presented with the same predictability as in our first study. In fact, (although lacking the multifarious noise of our chaotic example) the behaviour of the parts is unpredictably random.

So, from the perspective of the whole we have a predictable/ordered system and from the perspective of the parts we have a collection of unpredictable/random sequences.

To clarify this point, consider again that you are studiously watching just a single cell in an unknown CA. You have no visibility of any of the other cells surrounding it; you simply have knowledge of the behaviour of one single cell. It provides you with the following sequence:-

(c) 0101010101…

In this instance you rightly predict the next state to be zero and it turns out that you have been watching cell 18 in our first example (figure 3b). You then try the same experiment again with a different CA which this time provides you with a different sequence:-

(d) 0000000000…

In this instance you again predict zero to be the next state, however, you are wrong because you have been watching cell 1 in our third example (figure 5b). The behaviour of the individual cells within a CA containing a glider is unpredictable.

14 COMPLEXITY AND EMERGENCE

One may now collate the observations from the previous section into a coherent view of the three classes of behaviour found in complex systems (figure 6); allowing us to finally begin to formulate the complexity theoretic definition of emergence.

First however, let us pause for a moment to ponder a brief thought experiment; imagine, if you will, a giant chessboard of 5 x 5 squares.

Figure 6: Predictability within complex systems

Each square is 10 metres wide and surrounded by a wall 10 metres high. In the centre of each square, resting on the floor is a light-bulb. Every 2 minutes a siren sounds and the light-bulb in each room changes state according to a global rulebook and according to the status of the lights in the surrounding rooms. (This is, of course, a giant CA).

Inside each square we place a volunteer whose job it is to watch the light-bulb. They are unable to see the light-bulbs in any of the surrounding squares and are unaware of the rulebook governing the system. Instead, they simply have to watch their own light-bulb. We shall call these volunteers "the parts".

Finally, we place a volunteer in a specially constructed observation tower 100 metres above the chessboard. From this vantage point, the volunteer is able to see into all of the squares and is able to see all of the light-bulbs. We shall call this volunteer "the whole".

With everyone in place, we program the system of light-bulbs with a set of *'ordered'* behaviours (similar to the one we examined in figure 3) and leave it running for 3 hours. When the time is up, we pause it and walk around each of "the parts" asking them to predict what state they expect the light-bulb in their square to be when the next siren sounds. If anyone is able to provide us we an accurate prediction we give them 1 point. In this round "the parts" do very well indeed, and get a combined score of 25 points.

Next, we climb the ladder of the observation tower and ask "the whole" to perform the same prediction; giving him a point for every square that he is able to predict from his higher vantage point. He too scores very well, gaining 25 points.

For this round then, we declare a tie; and state that, for ordered behaviour, the whole is equal to the sum of the parts.

Next, we program the light-bulbs with a set of *'chaotic'* behaviours and after 3 hours we repeat our walk around "the parts" asking them again for the same predictions. This time, however, none of them are able to safely predict whether their light-bulb will be on or off and their combined score of 13 is no better than chance alone. We climb the tower and ask "the whole" for his predictions. He too states that he is not confident and scores himself 12 points.

For this round then, we declare a disappointing result; and state that, for chaotic behaviour, neither the whole nor the parts is able to provide us with any information over and above random chance.

Finally, we program the light-bulbs with a set of *'complex'* behaviours. After the 3 hours is up "the parts" do a little better than last time racking up a total score of 16 (thanks to the confidence of some of the volunteers whose light-bulb had been off for the entire duration of the experiment). With this we climb the ladder and ask "the whole" for his prediction. Surprisingly, he swiftly and confidently provides us with all 25 correct predictions.

For this final round we have a clear winner; and we state that, for complex behaviours, the whole is most definitely greater than the sum of the parts.

15 CLOSING

Emergence, it seems, is the process by which predictable behaviour arises from a complex collection of unpredictable parts; and it is exactly this kind of behaviour which is deemed *interesting* by Wolfram (1984) and which is highlighted by Chris Langton's region of complexity. In fact, it now appears that this complex space is, rather than lying at the transitional edge between order and chaos, better considered as a combinatorial overlap of the two opposing regions; wherein an ordered whole arises from unordered parts.

In considering what is gained by such predictability one might conclude that the answer is *information*. For example, during the third trial of our thought experiment, the whole contained more information than the parts. From this observation, one might wish to further conclude that emergence is the process by which new information becomes available within a complex system examined from a wider perspective.

The tentative hope of such an attempt at defining emergence from the perspective complexity theory, is to begin the process of framing the 'something' and the 'new'. It is time that we reduce the philosophical intuition and begin the construction of a more palpable field of study. In so doing it is hoped that we can, at last, begin to open our eyes to this recondite enigma, and start to turn the wonder into science.

16 REFERENCES

Ablowitz R. (1939) "*The theory of emergence*", Philosophy of Science (6) pp. 1-16

Baas N.A. (1994) "*Emergence, hierarchies and hyperstructures*", Artificial Life III, SFI Studies in the Sciences of Complexity (17) pp. 515-537

Baas N.A., Emmeche C. (1997) "*On E*mergence and Explanation", Intellectica (25) pp. 67-83

Bedau M. A. (forthcoming) "*Downward Causation and the autonomy of weak emergence*", Principia, special issue on emergence

Bedau M.A. (1997) "*Weak Emergence*", in Philosophical Perspectives: Mind, causation and world (11) pp. 375-399

Berlekamp E. R., Conway J. H., Guy R. K. (1982) "*Winning Ways for Your Mathematical Plays, Vol. 2: Games in Particular*", Ch 25, London: Academic Press

Campbell R.J., Bickhard M.H. (2002) "*Physicalism, Emergence and Downward Causation*", unpublished www.lehigh.edu/~mhb0/physicalemergence.pdf

Capra F. (1996) "*The Web of Life: A new synthesis of mind and matter*", Harper Collins

Capra F. (2002) "*The Hidden Connections*", Harper Collins

Cariani P. (1997) "*Emergence of new signal-primitives in neural systems*", Intellectica (25) pp. 95-143

Cariani P. (1990) "*Emergence and Artificial Life*", Artificial Life II, SFI Studies in the Sciences of Complexity (10) pp. 775-798

Chaitin G. J. (1975) "*Randomness and Mathematical Proof*", in From Complexity to Life, Oxford University Press

Crutchfield J.P. (1994) "*Is anything ever new? Considering emergence*", Complexity: Metaphors, Models and Reality, Santa Fe Institute Studies in the Sciences of Complexity (19) pp. 479-497

Crutchfield J.P., Mitchell M. (1995) "*The Evolution of Emergent Computation*", Proceedings of the National Academy of Sciences, USA 92:23 10742-10746.

Davies P. (2003) "*Towards an Emergentist Worldview*", in From Complexity to Life, Oxford University Press

Emmeche C., Køppe S., Stjernfelt F. (1990) "*Levels, Emergence and three versions of downward causation*", in Downward Causation: Minds, Bodies and Matter: Aarhus University Press

Feigenbaum M. (1978) "*Quantitative Universality for a class of nonlinear transformations*", Journal of Statistical Physics (19) pp 25-52

Forrest S. (1990) "*Emergent computation: self-organizing, collective, and cooperative phenomena in natural and artificial computing networks.*", Physica D (42: 1-3) pp. 1-11

Gershenson C. (2004) "*Introduction to Random Boolean Networks*", in Workshop and Tutorial Proceedings 9th Int Conf. on the Simulation and Synthesis of Living Systems (ALife IX) pp. 160-173

Holland J.H. (1998) "*Emergence: From Chaos to Order*", Oxford University Press

Johnson S. (2001) "*Emergence*", Penguin Press

Kauffman S. (1993) "*The Origins of Order*", Oxford University Press

Kubik A. (2003) "*Towards* a Formalization of Emergence", Artificial Life (9) pp. 41-65

Kuhn T. (1962) "*The Structure of Scientific Revolutions*", University of Chicago Press

Langton C.G. (1989), "*Artificial Life*", In Artificial Life. Addison-Wesley. pp. 1-47

Lorenz E. (1963) "*Deterministic nonperiodic flow*", Journal of the Atmospheric Sciences (20) pp 130-141

Langton C.G. (1990) "*Computation at the edge of chaos: Phase transitions and emergent computation*", Physica D vol. 42, pp. 12-37.

Lovelock J. (1979) "*Gaia: A new look at life on Earth*", Oxford University Press

May R.M. (1976) "*Simple mathematical model with very complicated dynamics*", Nature (26) 457

Mandelbrot B. (1977) "*The Fractal Geometry of Nature*", New York: Freeman

Maturana H., Varela F. (1980) "*Autopoiesis and Cognition: The Realization of the Living",* Boston Studies in the Phil. of Science (42)

Mitchell M., Crutchfield J.P., Das R. (1997) "*Evolving Cellular Automata to Perform Computations*", working paper, SFI

Mitchell M., Hraber P.T., Crutchfield J.P. (1993) "*Revisiting the Edge of Chaos: Evolving Cellular Automata to Perform Computations*", Complex Systems 7, pp. 89-130.

Mitchell M. (1998) "*A Complex-Systems Perspective on the "Computation vs. Dynamics" Debate in Cognitive Science",* Twentieth Annual Conference of the Cognitive Science Society

Morgan C.L. (1923) "*Emergent Evolution*", Northgate and Williams

Morowitz H. (2002) "T*he Emergence of Everything: how the world became complex*", Oxford University Press

Pepper S. (1926) "*Emergence*", Journal of Philosophy (23) pp. 241-245

Prigogine I. (1967) "*Thermodynamics of irreversible process*", New York: John Wiley and Sons

Prigogine I., Stengers I. (1981) "*Order out of chaos: Man's new dialogue with nature*", New York: Bantam

Rockwell T. (1995) "*A Defence of Emergent Downward Causation*", unpublished http://www.california.com/~mcmf/causeweb.html

Ronald E.A., Sipper M., Capcarrérre M.S. (1999) "*Design, observation, surprise! A test of emergence*", Artificial Life (5) pp. 225-239

Schneider E.D., Sagan D. (2005) "*Into the cool: Energy flow, thermodynamics and life*", University of Chicago Press

Schrödinger E. (1926) "*Quantisierung als Eigenwertproblem*", Annalen der Physik

Seeley T.D., Towne W.F. (1991) "*Collective decision making in honey bees: how colonies choose among nectar sources*" Behav. Ecol. Sociobiol. vol 28 pp 277-290.

Sipper M (1996) "Co-evolving Non-uniform Cellular Automata to perform Computations", Physica D vol. 92, pp. 193-208

Van Bertalanffy L. (1969) "*General System Theory: Foundations, Development, Applications*", New York: George Braziller

Van Gulick R. (2001) "*Reduction, Emergence and Other Recent Options on the Mind/Body Problem: A Philosophic Overview*", Journal of Consciousness Studies (8: 9-10) pp. 1-34

Waldrop M. (1992) "Complexity: The emerging science at the edge of order and chaos", Simon & Schuster

Wolfram S. (1984) "*Universality and complexity in cellular automata*", Physica D vol. 10

Wuensche A (1996) "*Attractor Basins of Discrete Networks*", unpublished D.Phil thesis, University of Sussex