

# INTRODUCTION TO PHILOSOPHY OF COMPLEX SYSTEMS: A

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PART A: TOWARDS A FRAMEWORK FOR COMPLEX SYSTEMS

## 1 INTRODUCTION

Every essay in this book is original, often highly original, and they will be of interest to practising scientists as much as they will be to philosophers of science — not least because many of the essays are by leading scientists who are currently creating the emerging new complex systems paradigm. This is no accident. The impact of complex systems on science is a recent, ongoing and profound revolution. But with a few honourable exceptions, it has largely been ignored by scientists and philosophers alike as an object of reflective study.<sup>1</sup> Hence the scientist participants; while the small band of concerned philosophers is well represented in this volume, scientists in the midst of creating the revolution are often better placed to reflect on it than others. (Needless to add, many more of both were invited than ultimately participated.)

In consequence, I have sired a cross-border bastard, properly belonging to neither philosophy or science but an inheritor, and supporter, of both. Being an ex-scientist turned philosopher, it is a bastard of my own kind. No matter its perceived legitimacy, a bastard is always a sign of fruitful productivity. And in this case the offspring is needed, for it is born into a time of revolutionary foment

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<sup>1</sup>For a substantial introduction see [Scott, 2004]. Scientists of course just get on with making and using specific innovations as needed, and that suffices. Honorable exceptions who have also reflected on the issues involved include the scientists Kenneth Boulding, Herbert Simon and Richard Levins (see [wwweb](#) information) and among philosophers include William Wimsatt and myself, all active across the last 4+ decades that mark the explosion of complex systems into the heartland of science. Wimsatt's work goes back to his early concerns with modelling methodology and explanation when confronted with complex systems and to some extent with systems ontology, with reduction/emergence bridging between them, now all reprinted and summed up in [Wimsatt, 2007]. [Hooker, 1978] showed that when the then-standard philosophical arguments about sense data in perception were embedded in a dynamical systems process setting, as the science already required, it re-cast them so as to make obvious their defects, [Hooker, 1981b, Part III] provided a first analysis of functional reduction in complex systems (subsequently updated in [Hooker, 2004; cf. this volume]) and [Hooker, 1995] a first attempt to recast philosophy of science itself as a dynamical systems process, see section 4.1.3 below.

whose constructive resolution is best eased forward by straddling both the philosophy and the science. This bastard will, I hope, be widely adopted and in turn prove fertile.

This present essay and its matching closing essay ([Hooker-b, this volume]<sup>2</sup>) are intended to be complementary and between them provide at least a first presentation of an intellectual framework for understanding the foundational and philosophical issues raised by the complex systems revolution. The present essay is designed to introduce and broadly review the domain of complex systems, with an eye to identifying the historical setting (section 2), the key systems properties at issue (section 3) and a collection of sub-domains that do not receive treatment in a dedicated essay (section 4). The closing essay is an attempt to systematically survey the specific components and issues that make up a scientific paradigm (section 5) and philosophy of science (section 6) that together comprise a foundational/philosophical analysis of the role of complex systems in science, as they currently appear.

Readers at least somewhat familiar with complex systems should find the essays to follow reasonably accessible, with references that invite further exploration. Those entering the field for the first time might like to first consult one or more of the books referenced at note 6 below and/or the websites referenced at [Hooker-b, this volume, note 15] (or any of the hundreds of other instructive books and websites available).

Ultimately, the goal is to develop mature foundations/philosophy of complex systems. But attempting this is premature at this time. First, despite enormous progress over the past 30 years, there is no unified science of complex systems. There are increasingly general insights and frameworks, the mathematical and operational mastery of chaos provides an early example, the current emergence of generalised network dynamics provides a contemporary example (cf. [Green and Leishman, this volume]). However, by themselves these do not a completed science make (cf. sections 4.2.6, 5.1.1 below), and at present they remain largely separate (if with multiple specific links — a typically complex situation!). Around them lie a patchwork of specific models and applications that presently remain irreducibly various. One aspect of the variability is the variety of complex systems phenomena engaged: in one application it may be counter-intuitive dynamics — such as the survival of cooperation in a sea of cutthroat competition — in another, self-organisation — such as rhythmic entrainment among food-stressed slime mould amoebae — in still another the onset of chaos — such as in local climate fluctuations — and so on. Another aspect of the variability is that characterising complex system principles is often a ‘wicked’ problem where the key dynamics generating a phenomenon is itself a function of the application conditions. To take a simple

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<sup>2</sup>Other essays in this volume are indicated by ‘[Name, this volume]’ and readers should turn directly to the indicated essay. The essays by Hooker in the volume are indicated by ‘[Hooker-a; b; c, this volume]’, a = present essay, b = closing essay, c = reduction/emergence essay. These references to Hooker in this volume are also entered in the essay bibliography to disambiguate the intended reference.

example, traffic jams on expressways may be caused by any of entry/exit rates, truck/car proportions, flow density, driver pathway correlations, etc. Moreover, the dynamics of jam formation for each of these conditions is significantly different. For instance, truck/car speed differential is important near lane-change originated jams but less important for high density braking-originated jams, and unimportant for pathway convergence jams. So there is no usefully generalisable, detailed dynamical rules for traffic jam formation. In sum, the empirical domain of complex systems is itself complex — at this time irreducibly complex!<sup>3</sup>

Irrespective of this developmental complexity, let us be clear about the extent of the complex systems revolution now taking place. When I trained in science (physics — PhD 1968) the contemporary icon for complex systems, chaos, was in process of discovery and few or no courses on complex systems were offered, those few problems considered involved several interacting bodies and were boxed as idiosyncratic special cases of applied mathematics. Today (2009) many of the most prominent scientific disciplines could not exist but for the complex systems models and methods on which they depend, among them synthetic and systems biology, climate science, control engineering, neurophysiology, developmental neuropsychology, astrophysics, geo-dynamics, traffic engineering, ... (cf. [Scott, 2004]). And there cannot be a single scientific discipline that has not now felt the complex systems winds of change blow through it to some extent — as this book testifies this now applies even to anthropology, Chinese medicine and warfare. The very way that science is transforming itself as complex systems penetrates it, is itself an excellent example of complex systems emergence through self-organisation, and one that, like many other instances, is re-defining the relationships between the emergent entity and the encompassing environment from which it emerged (see also section 4.1.3 below).

The scale and sweep of the change is truly vast — entire disciplines or sub-disciplines have come into being, departments and institutes of hundreds of scientists now exist that did not exist two decades ago, and Google entries under complex systems headings run into the tens of millions of pages — far too many for any individual to consult, even in a lifetime, thus creating an emergent reliance on systemic institutional structure and processes to generate scientific coherence, yet another facet of complex systems in science. (The same institutional structure needs to construct effective quality controls for generating this information deluge or, speaking impolitely, it is often a major challenge to winnow insight from the false, trivial and groundlessly speculative and the powerful crap detector required by all new, fecund fields is required here too.) Complementing this, policy analysis, industrial development and large scale financial planning all require complex systems modelling while vast enterprises in bio-agriculture, bio-medicine, manufacturing design and so on have arisen and flourished on the backs of these

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<sup>3</sup>And here a philosophical issue already raises its head: contrary to common opinion, a general model/theory of traffic jams will evidently be vaguer and less empirically precise and less explanatory than any of its specific sub-cases. So is scientific unification not to be preferred? See further [Hooker-b, this volume, section 6.2.6].

developments and are steadily transforming our lived world. Increasingly, people whose education does not include relevant competency in complex systems are excluded from science, policy and large scale business or find themselves increasingly dependent on those who have it.

Nor should the depth of the complex systems revolution be under-estimated. As the essays in this volume (including this one) attest, complex systems impacts every aspect of a science, from experimental design, what counts as evidence and the treatment of errors, through basic theoretical concepts of component, interaction, individuality, equilibrium (especially of dynamic versus static equilibrium), organisation and self-organisation, dynamic thresholds and irreversible form transitions, to deep limits on prediction and control and the relations of laws, explanation and confirmation to realisation conditions. (These notions will be explained in what follows.) And on a larger scale complex systems dynamical models naturally facilitate new disciplinary foci (such as systems biology) and new interdisciplinary interrelationships (such as synthetic biology and computational anthropology) while at the same time raising foundational issues concerning complexity and the representation of dynamics. In short, the complex systems-driven revolution is as deep as the revolutions in physics a century ago, but much wider in impact, even if they do not disturb our sense of fundamental reality in the same way.

What best to do? We have a revolution occurring in our midst, moreover one too complex and widespread for any one individual (a fortiori for me) to master in any detail across the board, and as yet lacking in any settled, or even well established, philosophical framework. Of course, I have tried to engage the sparse relevant philosophers (inevitably, not always successfully, for the usual practical reasons) and there are excellent essays herein that bear witness to those efforts. However, I had anyway concluded that, in the circumstances, to come to proper grips with the revolution and its challenges it would be necessary to engage the scientists themselves in the enterprise of reflecting on their own activities as they willy nilly develop complex systems based science. They are in the best position to comment on what the complex systems revolution involves for their discipline, and what its prospects are, and will remain so for many decades to come, even while complex systems philosophy of science develops.

Engaging eminent scientists has typically proven still more difficult than it was for philosophers, and understandably so: they are not only busy teaching, publishing and (these days) administering, as philosophers are, but have in addition to run their laboratories and field studies; moreover, they are rewarded for producing science, not for reflecting on that production, and it is often an intellectual wrench to take up the latter approach. Nevertheless, many scientists have willingly given their time and intellectual energy and many of the outstanding essays of this volume — essays that in themselves break new ground — have resulted from their collaboration.

In consequence, I have often played a more active role as editor than would be typical if this were a standard philosophy work, although many of the philosopher

authors too have happily engaged in rounds of drafting discussion. Editorial activism was always welcomed (and often at author request) as especially scientists sought (sometimes ‘fought’ would be more apt) to shift to the reflective mode and bring a complex maze of practical activity into focus. In doing so I have not sought to dictate the content of an essay (this attempt would anyway have been self-defeating) but to assist authors to organise, clarify and enlarge upon what they intuitively want to contribute. That collaboration often ran through many drafts, and it has been one of the most rewarding aspects of editing the volume. I have learned a lot along the way and had the privilege and joy of some of the most stimulating discussions of my career. My deep thanks to all those, scientists and philosophers, who gave so unstintingly to this pioneering volume.

The result is a volume quite different from the bulk of publishing in the area which typically focuses on a range of technical articles by scientists either developing particular techniques or applying them to practical situations, all material that could equally appear in the relevant disciplinary journals. Sometimes there will be added to front or rear a few very general articles about the ‘complexity world view’ or the like, at home in any general cultural discussion. This is true, e.g., of the recent Handbook on Simulating Social Complexity and the Encyclopedia of Complexity and Systems Science, both 2009 and no criticism of their primary aims and content. However, this volume fits instead exactly into the intermediate space left by such efforts: the detailed reflective discussion of the differences that employing the concepts, principles and methods of complex systems makes to the methodology and theorising of those sciences and the challenges posed to scientific metaphysics, epistemology and methodology arising therefrom. All the while it retains the connection to current examples and practices to vivify and discipline the reflections. At this stage it is premature to attempt a fully developed philosophy of science for the use of complex systems modelling, what might be achieved is briefly and schematically surveyed in [Hooker-b, this volume]. What this book does is provide the proper preliminary foundation of rich, higher order reflection on the changes and challenges as they are currently experienced in the sciences, material from which a more mature view will eventually emerge in the fullness of time — as is only fitting for a complex framework emerging from the complex adaptive process that is science.

Shalizi [2006] distinguishes four components to the content of complex systems work: **patterns** — the classification and study of the characteristic patterns in state space, e.g. period doubling before chaos onset, made by the trajectories of complex systems when they are displaying their distinctive complex dynamical behaviours; **topics** — the array of complex systems features (e.g. chaos) and exemplary cases (e.g. logistic population dynamics) frequently discussed; **tools** — the mathematical methods for data analysis that are appropriate for analysing data pertaining to complex dynamics, e.g. data mining techniques to discover relationships, especially in high dimensional, low density data distributions, and time series analysis (see [Ricklefs, this volume]); we are some distance yet from general tools for revealing system structure, though particular methods are developing

for local conditions; **foundations** — the mathematical foundations of complex systems dynamics, unfortunately currently very patchy, confined to theoretical fragments and particular applied models (see section 5 below). While this book is closest to the tools component, it is not primarily about any of these components — although some of its essays employ examples from patterns and topics and discuss issues that the tools and foundations raise. Rather, it is a reflection on what is distinctive to the conduct of science, especially as it pertains to metaphysics, epistemology and method, what this might amount to foundationally/philosophically, and what challenges are thus posed to science and philosophy.

Needless to say, there is yet much missing from this volume that would legitimately belong to it. Many domains contain numerous sub-domains of application of complex systems models. Biology, e.g., includes at least genome, cellular, multicellular, developmental, ecological and evolutionary modelling with further intra- and inter- sub-domain modelling specialities. But even were their separate inclusion practical (it is not) it would typically not add to the basic reflective issues thrown up. However, because of their prominence in their disciplines, I particularly regret the absence of essays on dynamical models in engineering, chemistry and social group dynamics. These and other disciplinary essays (e.g. on geodynamics, physiology, archaeology, business management and science itself) were vigorously sought but for one reason or another failed to materialise. While we lose the richness of their idiosyncratic responses to the entry of complex systems to their fields, most or all of the more general issues involved will have been well covered by the other essays. Some brief comments are made on most of these missing items in section 4.2 below, plus 4.1.3 (science) and [Hooker-b, this volume, section 5.3] (archaeology). Balancing these absences, on the other hand, are strong essays on Anthropology, Traditional Chinese Medicine, Military Policy and Planning and Public Policy and Planning that represent welcome surprises, areas beyond those normally attended to where the application of complex systems is delivering genuine insight and practical advantage.

Equally regretful is the absence of an essay on the primary mathematical issue raised by complex systems theory, namely the challenge it poses to standard analytical mathematical dynamics and the correlative disarray in unified mathematical underpinnings for complex systems. In my view, the suppression of this issue in many contemporary textbooks on analytical mechanics constitutes something of an intellectual scandal. There is currently no coherent mathematical framework for complex systems theory, as noted earlier there is instead a collection of diverse specific complex systems models and an equally diverse range of at best weakly interrelated mathematical research groups (see also 4.2.1 below). Perhaps this explains why it proved impossible to persuade anyone to write about it (and often even to respond), despite many invitations, especially to leading mathematicians. This is to be particularly regretted since the situation can instead be regarded as a stimulating challenge to future research. At any event the issue is unavoidable when trying to understand the nature of many key complex systems features, such as self-organised emergence. The basic issue is thus presented briefly, and

within my limitations, in the essay on reduction and emergence in complex systems ([Hooker-c this volume], cf. [Bickhard, this volume; Bishop, this volume]). But its consequences re-appear throughout the review of our several foundational ignorances in section 5.

This essay plus its complementary closing essay attempts to provide what is possibly the first comprehensive review of the philosophical-cum-foundational issues deriving from the impact of complex systems in science. The review is consciously schematic, deferring to the other essays herein to fill in domain and discipline specifics. My intention is to clarify where possible and start as many hares running as possible. And there are plenty of the latter, the essays are awash with topics worth investigating. Even so, they are also certainly incomplete.

Finally, while there will be plenty of controversial issues arising, I hope for the most part that my authorship per se plays no major intervening role, except perhaps in the reach/lack-of-reach and synthesis of material presented. Here there is a clear bias in these essays toward thinking in physical terms and using physical examples. I am trained as a physicist and there are fewer social examples than another researcher might use. (But natural science examples, being uncluttered with the complications of human capacities, are often also clearer.) The keenest lack is not a matter of domain emphasis, which I think has small effect here, but of tools: there is a relative absence of computational analyses and computational examples. Mea culpa, I can only point out that I do recognise computational analyses on occasion and refer the reader to the review by [Green and Leishman, this volume] for a glimpse of how remaining bias might be corrected. Beyond this, as fair forewarning to readers, my philosophical orientation makes itself felt in two particular ways in what follows. First, there is my preference for dynamical analysis over logical and semantic analysis when it comes to fundamental concepts and principles. I deeply believe that, especially in the domain of complex systems science, this is the only productive way forward. Correlatively, second, there is an occasional willingness to close off philosophical debate where I judge science has provided a clear dynamical indication of how best to proceed (but always flagged, so that debate may ensue).

## 2 HISTORICAL NOTES ON THE DEVELOPMENT OF COMPLEX SYSTEMS IN SCIENCE<sup>4</sup>

Preparations for the emergence of complex systems in science — both their study and use — have been over 150 years in the making. Even so, the explicit recognition of complex systems concepts, principles and models in science is a recent phenomenon. And the explosion of its application into widespread use, with all the consequences explored in this volume, is a still more recent matter of the last 25 years. Especially because of its sudden, late emergence its history is worth

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<sup>4</sup>The following historical discussion is excerpted and adapted with modifications and additions from [Hooker, 2009a, section C.5, 6], where it first appeared.

appreciating. Science has many long-term sub-processes running through it, not all fully coherent with its public consensus at any one time (or even in any one century). Any of these can unexpectedly burst forth to transform the way science is thought about and done. The rise of complex systems has been one of the more important of those processes. This is a reflection of the deep complexity of the science process, a self-reflexive application of complex systems ideas that has yet to reach a mature expression.<sup>5</sup> It is perhaps useful then to briefly rehearse a little of this historical background here. In what follows I stick to a simplified but multi-disciplinary, conceptual focus; there are plenty of other, complementary works that capture particular developments in more detail.<sup>6</sup>

The story is best told by beginning with the prior physics-based framework that essentially excluded complex systems, making the latter's appearance in science all the more surprising. For the roughly 260 years from the publication of Newton's *Principia* to the 1945 close of the Second World War, the defining characteristic of fundamental advance in physics was the understanding of dynamical symmetry and conservation. Symmetries are invariances under operations, the invariant quantity said to be conserved. For physics the fundamental symmetries are the invariances of — hence the conservation of — dynamical quantities under various continuous space-time shifts, for example conservation of linear (respectively, angular) momentum under shift in spatial position (respectively, orientation) or of energy under time shift. Noether gave systematic form to this in 1918 and showed that it was the invariance of the form of the dynamical laws themselves that was expressed. Collections of the same space-time shifts form mathematical groups and the corresponding invariances then form dynamical symmetry groups. For instance, Newton's equations obey the Galilean symmetry group. Symmetry forms the deepest principle for understanding and investigating fundamental dynamical laws [Icke, 1995; van Fraassen, 1989].

In addition to their general dynamical symmetries, many system states have additional symmetries, for example the lattice symmetries of a crystal. Within this framework thermodynamics emerged and thermodynamic equilibrium became the primary dynamical state condition for analytic dynamics of many-body systems because all residual motion is random, hence spatio-temporally stochastically symmetric. Moreover each stable equilibrium state is invariant with respect to transitory pathways leading to it (the outcome is independent of those initial conditions), so its history can be ignored in studying its dynamics. The dynamics itself can then be developed in a simplified form, namely in terms of local, small and reversible — hence linearisable — departures from stable equilibria, yielding classical thermodynamics. The only place for complexity here is simply the large number of particles involved, the least profound dimension of the notion (see

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<sup>5</sup>Some preliminary thoughts about it are found in section 4.1.3 below.

<sup>6</sup>These range from popularised expositions that still offer valuable introductions, such as [Gleick, 1988], to elegant mathematical reviews such as [Holmes, 2005]. Betwixt these lie many hundred good works, among them [Gell-mann, 1994; Goodwin, 1994; Kauffman, 1995; Layzer, 1990; Morowitz, 2002; Scott, 2004].



section 3 close).

The study of simple physical systems of a few components and of many-component systems at or near stable equilibrium supported the idea that the paradigm of scientific understanding was linear causal analysis and reduction to linear causal mechanisms, with the real as what was invariant under symmetry groups (a formal stability) or invariant to small perturbations (dynamical stability). Paradigm cases included 2-body solar system dynamics, engineering lever and circuit equations, equilibrium thermodynamics of gases.<sup>7</sup>

The philosophy of science evolved compatibly, focusing on determinism, universal a-temporal (hence condition-independent) causal laws, analysis into fundamental constituents then yielding bottom-up mechanical synthesis. To this was added a simple deductive model of explanation and prediction — deduction from theory plus initial conditions gives explanation after the event and prediction before it. Reduction to fundamental laws and separate contingent initial conditions became the basic explanatory requirement. This supports an ideal of scientific method as logical inference: logical induction from the data to form the most probably correct theory, deduction from theory for prediction and explanation, and deduction from data that conflict with prediction to a falsification of the predicting theory, or other assumptions. (However, it turns out (interestingly!) that neither the logical or the methodological situation is so simple; both scientific practice and rational method are, and must be, much more complex than this.<sup>8</sup>)

The scientific paradigm and the philosophy of science together constituted the intellectual framework of scientific orthodoxy for more than a century of scientific understanding. The evident fit between philosophy and paradigm supported the conviction that both were right, the logical clarity and elegance of the philosophy reinforcing that conviction. From within this framework, the greatest challenge is that of quantum theory to determinism and simple causality. But while this is a profound problem, the immediate theoretical challenge is also limited since the fundamental dynamical idea of a universal deterministic flow on a manifold characterised by its symmetries remains at the core (indeed is abstractly strengthened — see e.g. [Brown and Harré, 1988]).

That this orthodoxy could prove unduly confining became obvious first in biology, even if it had made earlier, tacit appearances in physics and engineering. With

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<sup>7</sup>See any of the many textbooks on these subjects. If all this seems somewhat impenetrable, it suffices to grasp the idea that symmetry, equilibrium and stability are the central structural features of dynamics in physics. On this framework see, for example, [Brading and Castellani, 2003; Icke, 1995; Stewart and Golubitsky, 1992; Van Fraassen, 1989] and on symmetry disruption by newer systems dynamics ideas see these and, for example, [Mainzer, 2005; Schmidt, this volume] and Brading's *Stanford Encyclopedia of Philosophy* entry at <http://plato.stanford.edu/entries/symmetry-breaking/>. Even with the common simplifying occurrence of symmetry and equilibrium, it is seldom appreciated that learning the dynamics of these systems would still have not been easy but for the fortunate presence of several other simplifying conditions, see [Hooker, 1994b].

<sup>8</sup>See classics of the time like [Nagel, 1961] on induction and reduction, and on falsification see [Popper, 1972]. For overview and discussion of the difficulties with this conception of the methodological situation see for example [Hooker, 1987 passim; 1995, ch.2].

respect to biology, Woese [2004] rightly remarks that the nineteenth century had seen the first wave of modern revolution: Pasteur and others had removed spontaneous generation and revealed the huge range of kinds of life, Darwin had brought their evolution within science, the cell had emerged and the idea of genes had begun to form (cf. [Sapp, 2003]). Subsequently, the formation period of modern biology, characterised by the rise of genetics and its incorporation into evolutionary theory, and the subsequent emergence of elementary molecular genetics in its support, was initially all understood within the physics-inspired orthodox framework. The simple fundamental laws of evolutionary population genetics and of molecular genetics that underlay them were held to provide the universal, unchanging causal reality underlying the apparently bewildering diversity of biological phenomena. The observed diversity was to be seen simply as reflecting a diversity of initial conditions independent of these laws, whether generated as exogenous geo-ecological events or as endogenous random mutations. Reduction to molecular genetics thus became a defining strategy. But many biologists resisted this orthodoxy, insisting that the telling characteristics of living organisms — metabolism, regeneration, regulation, growth, replication, evolution and developmental and behavioural teleology — could not informatively be brought within the confines of the prevailing orthodoxy (e.g. [Mayr, 2004]). The consequence of orthodoxy for biology is that either life is radically reduced to simple chemical mechanisms and then to applied traditional physics, or it has to be taken outside the paradigm altogether and asserted as metaphysically *sui generis*. Both were, and are, implausible positions.

These are undoubtedly the early theory building stages through which any science has to go as it laboriously assembles better understanding. Possibly this was itself intuitively understood by many scientists. Even so, there was enough dogmatic conviction in science, and certainly in philosophy of science, that the results were not pleasant for dissenters, who were denied a hearing and research funding and often ostracised. One might recall, as examples of this, the fates of Baldwin and Lamarck and others in biology, and of Piaget in biology and philosophy — all now being at least partially rehabilitated as the old simple dogmas break down — not to mention those in entire sub-disciplines such as embryology and ecology who were sidelined for many years before they have again returned to the forefront of scientific progress.

Yet all the while scientific work itself was quietly and often unintentionally laying the groundwork for superseding this orthodoxy, both scientifically and philosophically. To understand why this might be so one has only to contemplate what the previous paradigm excludes from consideration, namely all irreversible, far-from-equilibrium thermodynamic phenomena. This comprises the vast majority of the subject matter of interest to science, everything from super-galactic formation in the early cooling of the universe down to planet formation, all or most of our planet's geo-climatic behaviour, all phase change behaviour, natural to the planet or not, and of course all life forms, since these are irreversible far-from-equilibrium systems.<sup>9</sup> What all of these phenomena exploit is dis-equilibrium, spontaneous

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<sup>9</sup>Later static and dynamic equilibria will be distinguished, the latter co-existing with static

instability and symmetry-breaking (specifically, non-local, irreversible symmetry-breaking to form increased complexity). This is starkly clear for cosmic condensation: the universe begins as a super-hot super-symmetric expanding point-sphere, but as it expands it cools and differentiates, breaking its natal super-symmetry; the four fundamental forces differentiate out, their non-linearities amplifying the smallest fluctuation differences into ever-increasing structural features. In sum, all of this vast sweep of phenomena are characterised by the opposite of the symmetry/ stability-equilibrium paradigm.<sup>10</sup>

Thus it is not surprising that from early on, even while the elegantly simple mathematics of the symmetry/stability-equilibrium paradigm were being developed and its striking successes explored, scientists sensed the difficulties of remaining within its constraints, albeit in scattered and hesitant forms. Maxwell, who formulated modern electromagnetic theory in the later nineteenth century and sought to unify physics, drew explicit attention to the challenge posed by instability and failure of universality for formulating scientific laws. His young contemporary Poincaré spearheaded an investigation of both non-linear differential equations and instability, especially geometric methods for their characterisation. By the 1920's static, dynamic and structural equilibria and instabilities had been distinguished.<sup>11</sup> In engineering, non-linearity and emergent dynamics appeared in an analytically tractable manner with the entry of feedback and the development of dynamical control theory. Maxwell in 1868 provided the first rigorous mathematical analysis of a feedback control system (Watt's 1788 steam governor). By the early twentieth century General Systems Theory was developed by von Bertalanffy and others, with notions like feedback/feedforward, homing-in and homeostasis at their basis. Later Cybernetics (the term coined by Weiner in [1948]) emerged from control engineering as its applied counterpart at the same time as Walter [1950; 1953] was constructing his *Machina speculatrix* turtle robots and Ashby [1947] first introduced the term 'self-organisation'.<sup>12</sup> Classical control theory, which became

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dis-equilibrium to form fluid phenomena like hurricanes and all living systems. Phase changes illustrate structural instabilities, where the dynamical form itself changes during the transient trajectory.

<sup>10</sup>An early mathematical classic on non-linear instabilities referred to the old paradigm as the 'stability dogma' — see [Guckenheimer and Holmes, 1983, pp. 256ff]. See also the deep discussion of the paradigm by a pioneer of irreversible thermodynamics [Prigogine, 1967; 1980; Prigogine, Stengers, 1984] plus note 7 references. I add the phase-shift cosmogony of Daodejing, ch. 42, translated by my colleague Dr. Yin Gao, because the West has been slow to appreciate the deep dynamical systems orientation of this tradition in Chinese metaphysics, for instance in medicine [Herfel, *et al.*, this volume]:

The dao (the great void) gives rise to one (singularity)  
 Singularity gives rise to two (yin and yang)  
 Yin and yang give rise to three (yin, yang and the harmonizing force)  
 Yin yang and the harmonizing force give birth to the ten thousand things/creatures.

<sup>11</sup>Thanks to Birkhoff and Andropov, following Poincaré. Lyapunov's study of the stability of nonlinear differential equations was in 1892, but its significance was not generally realised until the 1960's.

<sup>12</sup>See [Weiner, 1948; Walter, 1950; 1953; Ashby, 1947; 1952], cf. <http://pespmc1.vub.ac.be/DEFAULT.htm> (Principia Cybernetica Web) and [Hofkirchner and Schafranek, this volume]

a disciplinary paradigm by the 1960's, forms the basis of the use of dynamical systems models in many contemporary systems applications.

In 1887 Poincaré had also become the first person to discover a chaotic deterministic system (Newton's 3-body system), later introducing ideas that ultimately led to modern chaos theory. Meanwhile Hadamard 1898 studied a system of idealised 'billiards' and was able to show that all trajectories diverge exponentially from one another (sensitivity to initial conditions), with a positive Lyapunov exponent. However, it was only with the advent of modern computers in the late 1960's that investigation of chaotic dynamics developed, for example for atmospheric dynamics (Lorenz). By the mid-1970's chaos had been found in many diverse places, including physics (both empirical and theoretical work on turbulence), chemistry (the Belousov-Zhabotinskii and like systems) and biology (logistic map population dynamics and Lotka-Volterra equations for 4 or more species) and the mathematical theory behind it was solidly established (Feigenbaum, Mandelbrot, Ruelle, Smale and others).<sup>13</sup>

Since then the story is one of exponential explosion of, and increasing complexity in, content. Bishop [this volume, section 2.4] recounts the complexities slowly uncovered in sensitivity to initial conditions and chaos in systems. Meanwhile, the identification and understanding of self-organised emergence shows no signs of global consensus yet. While many philosophers early on preferred 'change inexplicable from constituents' and the like (see e.g. [McLaughlin, 1992; O'Connor, Wong, 2002]), scientists prefer something less human-dependent, but without much agreement. Commencing from the most general of features and narrowing down there are, first, the common appeals to spontaneous symmetry breaking and failure of superposition (cf. [Landau, 1937; Anderson, 1972], followed by 'expresses logical depth' (see note 43 below) [Bennett 1985; 1992; Kauffman, 1995], 'better global system predictability than do the constituents'- [Crutchfield, 1994; Shalizi, 2001; *et al.*, 2004], 'exhibiting downward causation' — [Sperry, 1969; 1986; 1987; Campbell, 1974; Bickhard, 2000a; Goldstein, 2002], 'relatively macro constraint formation' — [Collier and Hooker, 1999; Hooker-c, this volume], these last three being cousins if the better predictability is because of the emergent constraints on the system, 'optimal prediction is simulation or reproduction' — [Bedau, 1997]

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on General Systems Theory. In control engineering Airy (1840) developed a feedback device for pointing a telescope, but it was subject to oscillations; he subsequently became the first to discuss the instability of closed-loop systems, and the first to use differential equations in their analysis. Following Maxwell and others, in 1922 Minorsky became the first to use a proportional-integral-derivative (PID) controller (in his case for steering ships), and considered nonlinear effects in the closed-loop system. By 1932 Nyquist derived a mathematical stability criterion for amplifiers related to Maxwell's analysis and in 1934 Házen published the *Theory of Servomechanisms*, establishing the use of mathematical control theory in such problems as orienting devices (for example naval guns). Later development of the use of transfer functions, block diagrams and frequency-domain methods saw the full development of classical control theory. For more details see, among many, [Bennett, 1986; 1993].

<sup>13</sup>For a reasonable coverage of books on complex systems dynamics over the period 1975-1995 see the \*ed works in the bibliography to [Hooker, 1995b] and for contemporary review see [Scott, 2004].

(cf. complexity as the amount of past information required to predict future system states, Shalizi), ‘requiring meta-modelling’ — [Rosen, 1985; Heylighen, 1991], and ‘expresses global semantics’ — [Pattee, 1968; 1997; Kubik, 2003] and ‘greater scope’ [Ryan, 2007]. See further [Bedau and Humphries, 2008; Boschetti, *et al.*, 2009; Holland, 1998]. Similar stories can be told about most of the other key complex systems features (see section 3 below for a list), and where only brief, vaguer stories are available it is because too little is yet known. The best introduction to the modern period is, therefore, the essays herein themselves.

Returning to the larger narrative, this historical account itself is unavoidably selective and sketchy, but it sufficiently indicates the slow build-up of an empirically grounded conceptual break with the simple symmetry/stability-equilibrium orthodoxy, and a corresponding background murmur of doubt and difficulty within the foundational/philosophical tradition. However the new approach often still remained superficial to the cores of the sciences themselves. In physics this is for deep reasons to do with the lack of a way to fully integrate instability processes, especially structural instabilities, into the fundamental dynamical flow framework (at present they remain interruptions of flows), the lack of integration of irreversibility into fundamental dynamics and the related difficulty of dealing with global organisational constraints in flow characterisation (see sections 3, 4 and 5 below). For biology all that had really developed was a partial set of mathematical tools applied to a disparate collection of isolated examples that were largely superficial to the then core principles and developmental dynamics of the field.

Nonetheless, by the late 1970’s it is clear in retrospect that science had begun to pull together many of the major ideas and principles that would undermine the hegemony of the simple symmetry/ equilibrium orthodoxy. Instabilities were seen to play crucial roles in many real-life systems — they even conferred sometimes valuable properties on those systems, such as sensitivity to initial conditions and structural lability in response. These instabilities broke symmetries and in doing so produced the only way to achieve more complex dynamical conditions. The phenomenon of deterministic chaos was not only surprising to many, to some extent it pulled apart determinism from analytic solutions, and so also from prediction, and hence also pulled explanation apart from prediction. It also emphasised a principled, as opposed to a merely pragmatic, role for human finitude in understanding the world.<sup>14</sup> The models of phase change especially, but also those of far-from-equilibrium dynamical stability, created models of emergence with causal power (‘downward’ causality — see above) and hence difficulty for any straightforward idea of reduction to components.<sup>15</sup> And, although not appreciated until recently, they created an alternative paradigm for situation or condition-dependent, rather than universal, laws.<sup>16</sup> Thus a new appreciation for the sciences of complex dy-

<sup>14</sup>The point being that any finite creature can only make finitely accurate measurements, independently of any further constraints arising from specific biology or culture; there is always a residual uncertainty and any sensitivity to initial conditions will amplify that uncertainty over time.

<sup>15</sup>See for example [Boogerd, *et al.*, 2002; 2005; Bruggeman, *et al.*, 2002].

<sup>16</sup>See further sections 3, 6.2.2 below; for the basic idea see [Hooker, 2004].

namical systems began to emerge.

Following this development a little further into contemporary biology as an example, and then briefly to psychology, will complete this invocation of a historical context for the essays to follow. The mid-twentieth-century period quietly set the stage for the undoing of geneticism: the assertion of a simple gene-trait-fitness model that effectively by-passes the cellular phenotype, with its biosynthetic pathways and multi-cellular physiological processes, as unnecessary to evolutionary explanation. The manner of undoing this paradigm paved the way for the more intimate introduction of complex systems methods into the heart of biology.

In mid-twentieth-century physics (1930-1970), Prigogine (following Schrodinger and Turing) worked on irreversible thermodynamics as the foundation for life. This generates a (macroscopic) metabolic picture in which the full internally regulated body, including each of its cells individually, is essential to life [Prigogine, 1967; 1980]. In the same period cellular biology was revived and underwent a rapid development. This was partly driven by new, biochemically based problems (understanding kinds and rates of chemical reactions like electron transport, etc.) and partly by new instrumentation (electron microscope, ultracentrifuge) that allowed much more detailed examination of intracellular structure and behaviour. In consequence, there was increasing molecular understanding of genetic organisation, especially development of RNA roles in relation to DNA, of regulator genes and higher order operon formation, and of the roles of intra-cellular biochemical gradients, inter-cellular signalling and the like in cellular specialisation and multi-cellular development. All this prepared the ground for envisioning the cell as a site of many interacting biochemical processes, in which DNA played complex interactive roles as some chemicals among others, rather than the dynamics being viewed as a consequence of a simple deterministic genetic programme. (The surprising modesty of the number of genes in the human genome, given our phenotypic complexity, emphasises the importance of the gene regulatory networks.) Genetics was replaced by ‘omics’ (genomics, proteomics, ... metabolomics, etc.).<sup>17</sup> These are the very ideas that, allied to the development of generalised network analysis emerging from circuit theory and chemical process engineering and elsewhere, would later underlie contemporary systems and synthetic biological modelling, now re-casting cellular biology and bio-engineering.<sup>18</sup>

During roughly the same period, Rashevsky and others pioneered the application of mathematics to biology. With the slogan *mathematical biophysics : biology :: mathematical physics : physics*, Rashevsky proposed the creation of a quantitative theoretical biology. He was an important figure in the introduction of

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<sup>17</sup>This term also stands for the technologies that provide data on these aspects of cellular function. See, for example, [Bechtel, 1989; Westerhoff and Palsson, 2004] and references, and the Omics symposia at <http://www.keystonesymposia.org/Meetings/viewPastMeetings.cfm?MeetingID=980&CFID=376546&CFTOKEN=248205721>.

<sup>18</sup>For an introduction to the field of systems and synthetic biology, see e.g. [www.systems-biology.org/](http://www.systems-biology.org/), <http://syntheticbiology.org/> and the IEEE Proceedings, systems biology, at [www.iee.org/Publish/Journals/ProfJourn/Proc/SYB/index.cfm](http://www.iee.org/Publish/Journals/ProfJourn/Proc/SYB/index.cfm). For a sense of the integration required from genes to cognition see Miklos (1993).

quantitative dynamical models and methods into biology, ranging from models of fluid flow in plants to various medical applications. That general tradition was continued by his students, among them Rosen, whose edited volumes on mathematical biology of the 1960's and 1970's did much to establish the approach.<sup>19</sup> In this tradition various physiologists began developing the use of dynamic systems to model various aspects of organism functioning. In 1966, for example, Guyton developed an early computer model which gave the kidney pre-eminence as the long-term regulator of blood pressure and went on to develop increasingly sophisticated dynamical network models of this kind. The next generation expanded these models to include intra-cellular dynamics. Tyson, for example, researched mathematical models of chemical systems like Belousov-Zhabotinskii in the 1970's, passing to cellular aggregation systems like *Dictyostelium* in the 1980's and to intra-cellular network dynamics models in the 1990's and this was a common progression.<sup>20</sup> See also the increasingly sophisticated models of timing (circadian rhythms)<sup>21</sup> and growth (L-systems) that complement more traditional growth models [Green and Leishman, this volume]. In this manner physiology has supported a smooth introduction of increasingly refined dynamical models into biology, providing a direct resource for contemporary systems and synthetic biology.

There has also been a correlative revival of a developmental perspective in biology, in embryology generally and early cellular differentiation in particular. This became linked to evolutionary 'bottlenecks' and evolutionary dynamics generally to form evo-devo as a research focus. Added to this was work on epigenetics and non-nuclear cellular inheritance, especially down the maternal line, and early work on enlarging evolutionary dynamics to include roles for communal (selection bias, group selection) and ecological factors, culminating in the wholistic 'developmental systems' movement.<sup>22</sup>

Ecology too has been studied as dynamic network (Lotka/Volterra, May, Levins and others), as an irreversible far-from-equilibrium dissipative flux network (Ulanowicz) or food-web energetics system (Odum), as a spatio-temporally differentiated

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<sup>19</sup>Indeed, as Rosen remarks, "It is no accident that the initiative for System Theory itself came mostly from Biology; of its founders, only Kenneth Boulding came from another realm, and he told me he was widely accused of "selling out" to biologists." On Rashevsky see, for example, [Rashevsky, 1964], <http://www.kli.ac.at/theorylab/AuthPage/R/RashevskyN.html>. For many years (1939-1972), he was editor and publisher of the journal *The Bulletin of Mathematical Biophysics*. For Rosen see [http://www.panmere.com/?page\\_id=10](http://www.panmere.com/?page_id=10) and notes 61, 64 and section 4.1.1 below. The quote comes from his *Autobiographical Reminiscence* at <http://www.rosen-enterprises.com/RobertRosen/rrosenautobio.html>.

<sup>20</sup>Among other resources see respectively <http://www.unc.edu/guyton/>, <http://mpf.biol.vt.edu/people/tyson/tyson.html>. Compare the work of Hogeweg, e.g. [2002a], [Hogeweg and Takeuchi, 2003] and see <http://www-binf.bio.uu.nl/master/>. For an eclectic but stimulating introduction to complex modelling of immune systems see <http://jason.brownlee05.googlepages.com/home22>.

<sup>21</sup>[Glass and Mackey, 1988; Kaplan and Glass, 1995; Winfree, 1987].

<sup>22</sup>See, for instance and respectively, [Solé, *et al.*, 1992; Raff, 1996; Raff and Kaufman, 1983; Goodwin and Saunders, 1989; Goodwin 1994; Jablonka and Lamb, 1995; Gray 1992; Oyama *et al.*, 2001], Gray's title itself indicating something of the macro intellectual landscape in which the idea emerged.

energy and matter flow pathway network (Pahl-Wostl) self-organising through inter-organism interaction (Holling, Solé/ Bascompte) and as an organized complex dynamic system employing threshold (bifurcation) dynamics, spatial organisation and exhibiting adaptive resilience (Holling, Walker and others), responding in complex, often counter-intuitive, ways to policy-motivated inputs.<sup>23</sup> All these features are found within cells, albeit more tightly constrained by cellular regenerative coherence, and fruitful scientific cross-fertilisation should eventually be expected, perhaps particularly with respect to the recent emphasis in both on understanding the coordination of spatial with functional organisation.

All of these scientific developments, still in process, work toward replacing black box geneticism with a larger model of a mutually interacting set of evolutionary/ developmental/ communal/ ecological dynamic processes.<sup>24</sup> Although still a collection of diverse models and methods, dynamical network methods are emerging across these disciplines as a shared methodological toolkit.<sup>25</sup> Combined, these developments present a picture of life as a complex system of dynamic processes running on different groups of timescales at different spatial scales, with longer term, more extended processes setting more local conditions for shorter term, less extensive processes while shorter term, local products accumulate to alter the longer term, more extensive processes, the whole interwoven with self-organised assembly of near-to-chaos criticality and resolutions of it.

A similar overall story could be told for several other subjects. As with biology, in each case the story is about replacing a ‘black box’ of internal quasi-formal elements, whose interrelations dominate the character of the whole process, with dynamical complex systems models that open up interactive modelling across the domain. For geneticism the elements were genes ( both for individuals and populations), their interrelationships determining traits for individuals and gene frequencies for populations. For the behaviourist psychology that dominated the first half last century, the elements were stimuli and responses, their association interrelations determining behaviour. Under criticism this model shifted to a functionally generalised Behaviourism, viz. computational cognitivism, whose elements were symbols and whose relations were logistic or formal symbolic programming. That model is still the orthodoxy today. Geneticism excluded or ignored what did not fit, namely the sciences of what embodied the elements and their interrelations — embryology, developmental and socio-biology and others. Similarly, behaviorist and cognitivist psychology excluded or ignored what embodied its associations or symbolic processes — developmental and neuro psychology and others.

Geneticism was undermined by the increasing emergence of dynamical models

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<sup>23</sup>See in rough text order, among many others, the following works and their references: [May, 1976; Ulanowicz 1997; Odum, 1971; Pahl-Wostl, 1995, Holling, 1992; Gunderson *et al.*, 1997; Gunderson and Holling, 1992; Solé and Bascompte, 2006; Dieckmann *et al.*, 2000; Cash *et al.*, 2006; Haila and Levins, 1992; Scheffer *et al.*, 2002] and further [Odenbaugh, this volume].

<sup>24</sup>Cf., for example, [Jablonka and Lamb, 2005] and note 22 references. See further section 6.2.4.

<sup>25</sup>For recent reviews see e.g. [Barabási, 2002; Boccaletti, *et al.*, 2006; Barabási and Bonabeau, 2003; Strogatz, 2001].



of what embodied the elements and their interrelations. Similarly, cognitivism is being undermined by the increasing emergence of dynamical models of what embodied the elements and their interrelations, e.g. by the interactive-constructive tradition in bio-psychology of Piaget [Piaget, 1971a; 1971b; Piaget and Garcia, 1989] (cf. Hooker [1994c]) and Vygotsky [1986] and Bickhard's Interactivism [Bickhard, 2005; 2008; Bickhard and Terveen, 1995]; the cognitive cybernetics tradition of Ashby [1947; 1952], Pask [1960; 1981], Cunninham [1972] and Cariani [1992; 1993]; the introduction and spread of neural network models from McCulloch and Pitts and Rosenblatt to Rummelhart *et al.* and on<sup>26</sup>; embodied agent robotics from Braitenberg [1984], to Brooks [1991] and Beer *et al.* [1993], Smithers [1995], Nolfi [this volume]; the related dynamical psychology tradition (Heath [2000], Ward [2002], Sheya and Smith [this volume], Van Orden *et al.* [this volume]); and through the embodied intentionality movement in philosophy from Merleau-Ponty [1962] to [Dreyfus and Dreyfus, 1986; Dreyfus, 1996] (cf. partial synthetic reviews by [Clark, 1997; Exteberria, 1998]). There is a similar story to tell about the neo-classical economic model of an agent (*Homo economicus*) as an internal bundle of expressed preferences and a market as an aggregate of these, each operating under a generalised Nash bargaining equilibrium process and being undermined by dynamical models of what embodies these processes.<sup>27</sup>

In both of these cases, as with biology, the entrance of complex dynamical systems models and methods did not simply replace one internal model with another. Instead it opened up the internal processes to much richer modelling of individuals and of their interactive relationships with other individuals, communities and ecologies (human and natural). This again indirectly undermines the hegemony of the simple symmetry/stability-equilibrium orthodoxy by supporting the development of an alternative suited to a complex dynamical world (sections 5, 6 below). And, as with biology, in doing so it opened up the prospect for rich cross-disciplinary integrations, from preference dynamics and decision psychology through collective interactions (for example through multi-agent network dynamics) to industrial ecology and evolution of market structure. We can even contemplate incorporating culture into this picture as a feature of a piece with it rather than as a separate box of memes. (Yet another internal box model like

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<sup>26</sup>See respectively [McCulloch and Pitts, 1943; Rosenblatt, 1958; Rummelhart, *et al.*, 1986]. See further history sites like [http://en.wikipedia.org/wiki/History\\_of\\_artificial\\_intelligence](http://en.wikipedia.org/wiki/History_of_artificial_intelligence) and [Churchland, 1989; 1995; Churchland, 1986; Hooker 1995a], among many, for wider review and references. However, connectionist methodology and rhetoric often retains the general internalist assumption that cognition is basically formal problem solving in a separable input-output processing unit that can be given a largely intrinsic characterisation.

<sup>27</sup>See e.g. econophysics [Rickles, this volume], evolutionary economics [Foster, this volume], while [Anderson, *et al.*, 1988; Arthur, *et al.*, 1997; Blume, Durlauf, 2006] offers a general review. Despite its recent suppression, the dynamical approach has a long history, see e.g. [Roos, 1927], and is now entering orthodox economic discussions from every side, see e.g. the Journal of Economic Dynamics and Control [http://www.elsevier.com/wps/find/journaldescription.cws\\_home/505547/description#description](http://www.elsevier.com/wps/find/journaldescription.cws_home/505547/description#description), and the Society for Economic Dynamics and their journal at <http://www.economicdynamics.org/index.html>.

those above.)<sup>28</sup> In short, in place of a dis-unified collection of assorted boxes of elements, dynamical complex systems approaches offer a rich, unified conception of the world and its science based on interrelating the dynamical models being employed in each — albeit a complex unity of differing but mutually interacting processes and levels governed by condition-dependent laws (cf. section 3 below).

### 3 CONCEPTUAL NOTES ON COMPLEXITY

It is now a good idea to obtain some grasp on what complex systems are. Unhappily, as noted earlier, there is currently no unified theory available, nor do we know how to systematically interrelate all the characteristic properties involved. Grimly, this disunity opens the way to an opposite affliction, mis-placed simplicity: too often when discussing complex systems only a select few characteristics are considered (most commonly, just chaos) and the rest ignored. In consequence, discussion is often inadequate because too narrowly based. Similarly, simplistic notions of complexity are too often assumed, e.g. that it is just showing counter-intuitive or unpredictable behaviour, or having many independent components and so requiring a long description. What follows is an informal rather than a technical exposition, although technical remarks appear. It is made with the aim of surveying an adequate range of system features entering complex systems, but also with an eye on the issues they raise for understanding complexity and complexity science.

The complex systems that constitute our life world are characterised by deterministic dynamics that manifest some or all of the properties in the following list. Roughly, properties lower on the list are increasingly richly possessed by living systems and present increasing contemporary challenges to our dynamical understanding. The properties are briefly characterised, in order of appearance.

- Non-linear interactions; non-additivity;
- Irreversibility;
- Constraints — holonomic and non-holonomic;
- Equilibria and Stabilities — static and dynamic;
- Amplification; sensitivity to initial conditions;
- Finite deterministic unpredictability;
- Symmetry breaking; bifurcations; self-organisation; emergence;
- Constraints — enabling and coordinated;
- Intrinsically global coherence;
- Order; organisation;
- Modularity; hierarchy;

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<sup>28</sup>For the internal-box-model tradition in biology, psychology and sociology see [Christensen and Hooker, 1998], for preliminary thoughts about modelling culture dynamically see [Hooker, 2002] and section 4.1.2 below. For a complementary conception of integrated or holistic dynamical agency see note 51 references. Culture has also been introduced to evolutionary processes as simply a selection bias or similar ‘external factor’; insofar as these processes are dynamically modelled they also contribute to this picture, albeit less fully.

Path-dependence and historicity;  
 Constraint duality; super-system formation;  
 Coordinated spatial and temporal differentiation with functional organization;  
 Multi-scale and multi-order functional organisation;  
 Autonomy; adaptation; adaptiveness; learning;  
 Model specificity/model plurality; model centredness;  
 Condition-dependent laws.<sup>29</sup>

The diversity and domain-specificity of these properties explains the diversity of notions of complexity, self-organisation, etc. The challenges to understanding that these properties continue to pose reduces hope for any unified account of the complexity domain in the near future, although progress continues to be made (see below).

Just as there is no canonical list of complex systems properties, many of these terms have no canonical expositions — recall views of emergence, above. (This is another of the complexities of the complex systems field.) The proper exposition of many of these terms might each take an essay and it will be a kind of reflexive manifesting of the diversity of the field to review what features, under what descriptions, this volume’s authors use. I have no wish to impose expository order here. (Readers should feel free to use the expositions as a base from which to explore alternative conceptions, including ones that contradict opinions expressed below.) Nonetheless, a bat-roost squawk of disparate terms left unattended may confuse readers dipping their toes into new domains. Moreover, while the gists of some of these terms are well enough known, some terms that are in common usage are often wrongly considered well known. Instead, they present ongoing challenges to understanding (e.g. self-organisation, emergence and organisation) and/or are vague or misunderstood (constraint duality, path-dependence, autonomy, model centredness). So, in the following the gists of all these terms will be briefly provided, as a general orientation (only) to the phenomena and issues subsequently discussed in this essay and the essays to follow.

**Non-linear interactions and non-additivity.** An interaction is *non-linear* in some variable  $v$  if the interaction force does not vary proportionately to  $v$  (F linearity:  $F(kx) = kF(x)$ ,  $k$  a number). Gravitational force, e.g., is spatially non-linear since it varies as the inverse square of the interaction distance ( $G(kr) = k^{-2}G(r)$ ). Interaction linearity yields linear dynamical equations describing the system,  $F/m = d^2x/dt^2 = a^2x$ , yielding exponential ( $a^2 > 0$ ) or oscillatory ( $a^2 < 0$ ) motion, respectively  $x(t) = Ae^{at}$ ,  $Ae^{iat}$ . These are characterised by additivity: any numerical combination of solutions (e.g.  $Ae^{at} + Be^{at}$ ) is also a solution. No complex dynamical behaviour is possible. Conversely, interaction non-linearity

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<sup>29</sup>This list elaborates on that in [Herfel and Hooker, 1999]. I happily acknowledge Herfel’s various contributions to my understanding of them at that time. An abbreviated intermediate version without most commentary appeared in [Hooker, 2009a, section D.7]. Another list appears in [Bishop, this volume]. Bishop’s list and mine, together with the conclusions we draw from them, were arrived at mutually independently.

yields non-linear dynamical equations characterised by *non-additivity*: numerical combinations of solutions are in general not solutions. (This is essentially because non-linearities ensure that the consequence of an increase or decrease in some quantity is not proportional to it.) Non-additivity is a necessary condition for complex dynamical behaviour.<sup>30</sup>

**Irreversibility.** A process that is reversible can also be run backwards while still satisfying the same laws. Classical dynamics is time-reversible in this sense. Every dynamically possible process running forward is equally possible running backwards. But virtually all real processes are dissipative, the energy they degrade in quality and shed as waste during the process cannot be retrieved (e.g. because it is converted to heat and distributed randomly throughout the universe) so that they cannot be run in reverse. They also will not persist unless a supply of sufficiently high quality energy, typically in requisite material forms, is available to continually renew their dissipative processes. Hence they are inherently open systems. Here only very small, brief changes may be approximately reversible, a condition especially obtaining near a dynamical equilibrium. Many, not all, examples of complex dynamics, but all those concerned with living systems, are of this kind.

**Constraints — holonomic and non-holonomic.** Constraints on a dynamical process are those limitations on the relationships among its variables that arise from the imposed physical conditions in which the process takes place. A marble rolling in a bowl, e.g., is confined to the surface of the bowl, whereas a small spacecraft has no such constraints, though both move under local gravitational forces. A system's effective degrees of freedom are those provided by its inherent variabilities (its dynamical variables) minus those removed through constraints.<sup>31</sup> A dynamical explanation consists in deriving the behaviour in question from a model of dynamical variable interrelations, constraints and initial conditions.<sup>32</sup>

<sup>30</sup>See also [Bishop, this volume, section 2.2] on failure of superposition (= additivity). But its failure is not a sufficient condition for complexity, as the example of 2-body gravitational motion shows. We currently have no general account of which kinds and combinations of non-linearities will yield which classes of complex systems since interesting complex systems can be governed by relatively structurally simple, 1 or 2 variable, equations (e.g. 1-variable logistic reproductive and 3-body gravitational systems) as well as by more complex equations, while some algorithmically very complex non-linear systems (for example, a gas) generate no interesting complex behaviour.

<sup>31</sup>It is possible in principle to also constrain a system's parameter ranges — in effect, to constrain the range of quantitative forms its dynamics can take — but this is difficult and rare for all but artificial systems set up for this purpose. The net effect of such constraints will still appear as (indirect, often extremely complex) constraints on variables.

<sup>32</sup>The initial conditions fix its particular trajectory from among the possible ones. Constraints are taken to include limiting constraints (e.g. that interaction forces go to zero at infinite separations). These are often labelled the system 'boundary conditions'. However 'constraints' is both more faithful to the mathematical structure of dynamics and more general since it continues to apply even when boundaries are diffuse or uncertain (cf. [Bishop, this volume, section 3.5] and when the constraints penetrate inside accepted boundaries (e.g. an externally applied electric field, the zero limit for distant forces). On dynamics see further [Hooker-c, this volume].

As the marble rolling without and with friction respectively shows, constraints may apply to both reversible and irreversible processes and are typically required to characterise specific processes, e.g. in a cell. Currently, we can only form general analytic dynamics, the Lagrangian/Hamiltonian dynamics, for systems that do not work on their constraints. The core of these in turn is formed by systems also having holonomic constraints (roughly, constraints that are purely a matter of space-time geometry and independent of the system's dynamical states) and are energy conserving. There are various simple extensions of this core theory into the non-holonomic, non-conserving domain but they remain special cases. It is precisely these features that complex non-linear irreversible systems lack. E.g. a river running between sand or gravel banks has non-holonomic constraints (the banks) which it alters through doing work on them and thus dissipating (not conserving) its energy. Similarly, a group of closed self-reproducing processes (e.g. cell metabolism) must do work on their many constraints in order to recreate them, while many dynamical bifurcations (e.g. boiling) are initiated in this way. *Prima facie*, all of these systems fall outside the scope of analytical Lagrangian dynamics.<sup>33</sup>

**Equilibria and stabilities — static and dynamic.** Qualitatively, some aspect  $A$  of a dynamical system is in equilibrium if (and only if) there is no net force acting on the  $A$  aspect of the system (its  $A$  forces are in balance) and there are thus no net  $2^{nd}$  order rates of change (accelerations) in  $A$ . Across the range of possible  $A$  choices an important distinction is then drawn between static and dynamic equilibria, that is, between cases where the time invariance concerns state parameters and variables ( $A =$  system state) and cases where it concerns process parameters and rate variables ( $A =$  system processes). Static equilibria require no energy input or output to persist, e.g. a crystal at rest. Dynamical equilibria typically require an irreversible ordered energy (negentropy) flow to sustain them, e.g. water flow to sustain the wave structure of river rapids, together with appropriate waste (degraded or entropic) outputs, e.g. turbulent water. For living systems there is water, food and hydrogen or oxygen input flow to sustain them and heat and chemicals as waste outputs. For these and other dynamically stable systems energy-material flows act to stabilise the system processes so that, for small disturbances that do not affect the underlying flows, these systems will behave as if they have static equilibria in these flow variables. In other respects however, such as river flows acting on river banks and metabolism producing cellular aging, the system may do work that alters, and eventually undermines, its dynamic equilibria.

Equilibria of any sort are stable, meta-stable or unstable. An equilibrium in some aspect  $A$  is stable, with respect to some class of disturbances (perturbations)  $D$ , if (and only if) its response to any disturbance from  $D$  is to soon return near

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<sup>33</sup>See, among many, [Bloch, 2003] and further discussion in [Hooker-c, this volume]. As Bloch demonstrates, it is possible to control non-holonomic systems even where we have no analytical dynamics for them, because we can still locally model the dynamical behaviour.

(including exactly) to its original  $A$  condition under its own dynamical processes and remain there. An equilibrium is unstable to a class  $D$  of disturbances if it does not return near to its original  $A$  condition and it is meta-stable to  $D$  if it is stable for some disturbances from  $D$  and unstable for others.<sup>34</sup> The closed set of states a system repeatedly traverses when at equilibrium is its attractor (the marble's rest point is a point attractor, if it circled frictionlessly around that point but up the basin wall it would be a cyclic attractor) and the wider set of states it can pass through while still returning to its attractor is its 'attractor basin' (the bowl provides a literal attractor basin).<sup>35</sup> A complex dynamics may generate several different equilibria of various stabilities (attractor basins of various shapes) either directly intersecting or connected by transient paths (where small disturbances may change its destination, cf. rolling on horizontal surfaces) plus other transient paths that do not end. This 'attractor landscape' is a system's dynamical signature, expressing its dynamical form.<sup>36</sup> A system that remains within a single attractor landscape is structurally stable (= autonomous dynamics in mathematical parlance) and otherwise is structurally meta- or un- stable. While mathematical dynamics typically assumes structural stability, many complex systems are structurally unstable (= bifurcate in mathematical parlance), e.g. exhibiting phase changes.

**Amplification.** Transient paths aside, a disturbance to a system at equilibrium will have one of three consequences: leave it within its current attractor basin, push it into another attractor basin, or transform the attractor landscape, leaving the system in an attractor basin in the new landscape.<sup>37</sup> In the first case, the

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<sup>34</sup>Often presentations will use a simplified form by taking  $A$  to be all state parameters and variables or all process parameters and rate variables and taking  $D$  to be all disturbances, so that stability is global stability and so on, but relativising the notion to an aspect  $A$  and a class  $D$  of disturbances provides for a more precise and richly structured, and realistic, account. Note that this formulation holds for both static and dynamical equilibria, it is just that in the static case it applies to a set of state parameters and variables while in the dynamical case it will apply to a set of process parameters and rate variables. To obtain a quantitative notion it is necessary to specify how near a return is near enough and how soon the return is soon enough, and perhaps how far it can wander (how much it can change its equilibrium parameter and variable values) before returning and how easy/hard it is to create that wander with a perturbation (how much resistance it has). These are details here, but they can be useful for various purposes and are required in any rigorous analysis — e.g. see [Brinsmead and Hooker, 2006] on ecological resilience.

<sup>35</sup>In 'bowl' terms, for a class  $D$  of disturbances of energy less than the bowl height, equilibria can be stable (= simple bowl-like attractor basin, the system response to all perturbations is to return to the attractor), meta-stable (= a bowl much shallower in some directions than others, the system response to some sufficiently energetic perturbations escapes the bowl and does not return to the attractor) and unstable (= atop an inverted bowl, the system response to all perturbations is to not return to the attractor). For an introduction, among many, see [Lorenz, 1997].

<sup>36</sup>A dynamics for which superposition holds [Bishop, this volume], that is, a linear dynamics (see above), has no attractor basins, hence no equilibria, simply a 'flat' landscape filled with transients. (Technically it is everywhere in a degenerate 'neutral' equilibrium, remaining in whatever state it happens to be in initially.)

<sup>37</sup>Including transients complicates the story without adding anything essential.

disturbance will be suppressed — negatively amplified (amplified down) — as the system returns near to its original state. In the other two cases the disturbance will be augmented — positively amplified (amplified up) — as the system departs from its original state. Amplification is the norm in non-linear systems.

**Sensitivity to initial conditions.** Non-linearities permit small differences in system state to be amplified into large differences in subsequent system trajectory. This is sensitivity to initial conditions. For instance, a system may be poised near the threshold of changing either attractor basin within the same landscape or changing landscape, so that a small disturbance is amplified to produce a larger change. And while systems left by disturbances inside the same attractor basin are insensitive to initial conditions in respect of their ultimate destination, they may still be locally sensitive to the path taken back to the equilibrium attractor.<sup>38</sup> Sensitivity to initial conditions is as common as amplification, but under certain conditions it takes a special form where a ‘strange attractor’ is formed in which motion is said to be chaotic because it occurs at random (in certain respects). However, the motion remains deterministic and, far from being more disordered than a normal attractor, is best viewed as super-ordered since every point within it may manifest sensitivity to initial conditions. The randomness is confined to trajectory locations sampled across the attractor and the like. Indeed, measures of chaotic system states show statistical distributions with ‘fat tails’, that is, with events that would be rare and lie far out from the mean were the processes fully random now showing up much more often [Rickles, this volume]; this is to be expected since the trajectories remain confined to the strange attractor, reflecting their internal interdependencies. Such phenomena are characteristic of chaos but are not confined to that condition, they may occur wherever subtle correlation is combined with quasi-randomness.

**Finite deterministic unpredictability.** Systems manifesting sensitivity to initial conditions present the problem that small uncertainties (including errors) in initial conditions may be amplified into large subsequent uncertainties in system location and trajectory. That is, system predictability is limited by knowledge of initial conditions. How severe a limitation this is in practice, and in what respects, depends on the amplification processes involved. In particular, while prediction that a system’s state will remain within a strange attractor is often legitimate, knowledge of location within the attractor can be quickly lost (though not always). Conversely, since systems showing sensitivity to initial conditions can be significantly influenced using only small signals (disturbances), then so long as the relevant state conditions can be distinguished, these conditions can be used to

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<sup>38</sup>Think of a marble rolling in a bowl with a pinpoint protuberance on its side surface. As these cases all show, sensitivity is strictly relative to the specified magnitudes of the disturbances. On this and following notions see also [Bishop, this volume].

sensitively guide or control them.<sup>39</sup>

**Symmetry breaking.** A symmetry is an invariance under an operation, e.g. the molecular structure of a cubic crystal is invariant under spatial shift along any axis, classical dynamics is invariant under reversal of time. Symmetry breaking occurs when an existing symmetry is disrupted. If water or another fluid is heated from below in a pan, e.g., then its previous complete kinetic symmetry (same random motion profile of molecules throughout the pan) is broken vertically as layers nearer the bottom heat up while those at the top remain cooler, passing the applied heat upward by conduction. This already changes the dynamical form of the system, from a stable dynamic equilibrium maintained by internal molecular collisions producing no net macro force to a stabilised dynamic equilibrium maintained by an irreversible vertical transmission of heat (kinetic energy). If the applied heat is increased there comes a point where rolling boiling sets in, conduction is replaced by convection and the fluid breaks up horizontally (and vertically) into convection cells, each matched to its neighbour along its boundary. This change corresponds to the breakdown of previous horizontal symmetry and is again maintained by the (increased) heat flow. In each symmetry breaking the orderedness and complexity of the system behaviour increased, and this is typical. Symmetry breaking may be spontaneous, that is, brought about by the system's own dynamics, or imposed, as in the heating example above. Spontaneous symmetry-breaking transitions are assumed to account for all the emergence of order and complexity in the universe since the super-symmetry of the big bang.<sup>40</sup>

**Bifurcation.** A bifurcation occurs when a structural instability in a system leads to a change in its dynamical form, that is, a change in the structure of its attractor landscape. There are many dynamically different ways in which this can occur, broadly classified as either local — where the form changes continuously as some dynamical parameter or parameters continuously vary — or global changes that involve more complex shifts.<sup>41</sup> Among the latter are phase transitions (e.g. gas to liquid, liquid to solid, or reverse), including critical point transitions (e.g. si-

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<sup>39</sup>Satisfying the qualifying clause is of course the difficulty. In this respect, there has been claimed to be an ideal condition for generating complex behaviour (strictly: computational capacity in a cellular automaton) and that is near to the chaotic condition, where there are multiple sensitivities, but not fully chaotic (in a strange attractor) where there are too many of them. This is edge-of-chaos criticality. Van Orden *et al* [this volume] give it a large role. However, this idea has also been criticised. See [http://en.wikipedia.org/wiki/Edge\\_of\\_chaos](http://en.wikipedia.org/wiki/Edge_of_chaos) for a summary and references.

<sup>40</sup>See [Landau, 1937] and the classic [Anderson, 1972] and note 7 references.

<sup>41</sup>See, e.g., <http://www.scholarpedia.org/article/Bifurcation>, including [Guckenheimer and Holmes, 1983; Humphries, 1994] on the Ising model, and the International Journal of Bifurcation and Chaos. For a local example, imagine how the motion of the marble rolling across a round-bottomed plastic bowl changes when a screw is attached to its base at some point and is either lowered to create a local basin or raised to create a local hill in the bowl contour. The marble dynamics changes as the bolt shifts away from neutral, so the bifurcation parameter is the height of the bolt.



multaneous transitions among gas, liquid and solid states), where changes can be discontinuous and uncomputable, essentially because fluctuations on every scale up to that of the whole system are simultaneously possible. While we can study mathematically the conditions under which a bifurcation occurs, beyond the simplest cases we typically have no dynamical mathematical analysis of the process of the change. Rather, the conditions of occurrence are deduced, where possible, by matching up characterisations of the antecedent and subsequent dynamical states, e.g. in terms of parameter changes across the bifurcation threshold.

**Self-organisation.** Self-organisation occurs when a system bifurcates, sufficiently under its own dynamics, to a form exhibiting more ordered and/or more complex behaviour. The molecular motion in a heated pan of water shifting from conduction through random collisions to cellular convecting, provides a core intuitive example. By contrast the reverse bifurcations as heat is reduced to the water, equally dynamically transforming, would not normally be considered self-organisations (they might be considered self-disorganisations). Since the condensing of molten iron to form a solid iron crystal is also considered self-organisation it is clear that self-organisation has little to do with organisation proper, since an iron crystal is too ordered to be significantly organised (see below). Many self-organised states could also be brought about through external manipulation; e.g. it is possible to build up an iron crystal lattice by spraying iron ions a few at a time on a template. While the outcome is the same, here the active ‘self’ is missing. All things considered, it is probably most useful to consider self-organisation to occur where (and only where) a system bifurcates, sufficiently under its own dynamics, so as to bring to bear an additional system-wide constraint (or at any rate an additional multi-component, that is, relatively macro, constraint).<sup>42</sup>

The formation of a new relatively macro constraint, however brought about, creates a new level proper in the system, since the constraint now filters out more microscopic relation detail incompatible with it. The iron crystal lattice, e.g., filters out thermal fluctuations and many external perturbations, dissipating their energy as lattice vibrations. (Otherwise the constraint would not be stable against

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<sup>42</sup>See [Hooker-c, this volume]. Some may prefer to refer to the formation of a new ‘top-down’ constraint or to ‘downward’ causation [Campbell, 1974; Bickhard, 2000a], to emphasise the new dynamical entity as outcome, its component dynamical interrelations constrained by its macro dynamical form. Others may instead prefer to refer to mutually constrained behaviour in order to emphasise that the emergent dynamical change is produced by the way interactions among constituents issue in mutual constraint. Cf. [Craver and Bechtel, 2007; Emmerche, *et al.*, 2000; O’Connor and Wong, 2002]. But these two are in fact equivalent, since the mutual constraint is macroscopically real, producing new forms of work. However, what counts as “sufficiently under its own dynamics” to justify the ‘self’ in self-organisation can be a vexed matter. The pan of heated fluid counts as self-organised because, while the applied heat is key to ‘forcing’ the dynamical changes, it is applied sufficiently externally to the fluid dynamics. If we deliberately add species to an ecology until it achieves a certain resilience to drought, on the other hand, it would not be considered to *self*-organise that dynamical form transition. The system could also not be considered to simply have been organised either, because the outcome may not be increased organisation — see ‘organisation’ below. (Though, speaking colloquially, we could say that we ‘organised’ it, we would only sometimes be technically correct.)

microscopic-originated perturbations and similar external disturbances.) The iron becomes a 2-level system, (1) that below the level of the lattice, the individual ions and electrons, obeying their dynamical interaction laws, and (2) that at the lattice level with its fermi conduction band where electrons stream through the lattice, the lattice collectively vibrates, and so on. This is a dynamically well-defined and grounded notion of ‘level’, all other uses are for gravitation (e.g. level table) and measurement (e.g. flood level) or are metaphorical (e.g. abstraction level) or confused. The constraint sense of ‘level’ is the only use made of the term in this essay and [Hooker-b,c, this volume].

**Emergence.** When the outcome of dynamical interaction among system components is surprising or unexpected or too complex to readily understand, scientists are apt to talk about emergent patterns. However this is a vague, shifting and subjective approach. (In colloquial usage ‘emerge’ often means no more than ‘becomes perceptible’.) Limiting emergence to the appearance of a phenomenon that could not have been predicted from knowing only the pair-wise dynamical interactions of components sharpens it somewhat. But this still ties the definition of what is a physical property to a non-dynamical criterion (prediction). Indeed, since prediction is often limited, many behaviours would count as emergent just on these grounds. But there is instead the alternative option of pursuing a dynamical criterion. A clear, wide criterion would be to identify emergence with bifurcation generally, a clear narrower one would be to identify it with just self-organisation. In each case a new dynamical form does come into being. Other criteria are possible (see section 2 above) but these are the clearest, simplest dynamically grounded ones. And, if the epistemic and semantic criteria are removed from the section 2 list, then plausibly the remaining criteria all work off one or other of these two dynamical criteria. [Hooker-c, this volume] argues for the wider usage on the grounds that emergence is concerned with new dynamical character as outcome, not the process producing that result.

**Constraints — enabling and coordinated.** The term ‘constraint’ implies limitation, most generally in the present context it refers to limited access to dynamical states. Equivalently, it means **reducing degrees of freedom by limiting dynamical trajectories to sub-sets of state space.** This is the common *disabling* sense of the term. But constraints can at the same time also be *enabling*, they can provide access to new states unavailable to the unconstrained system. Equivalently, by coordinately decreasing degrees of freedom they provide access to dynamical trajectories inaccessible to the unconstrained system. Thus a skeleton is a disabling constraint, for example limiting the movements of limbs (cf. an octopus), but by providing a jointed frame of rigid components for muscular attachments it also acts to enable a huge range of articulated motions and leverages, transforming an organism’s accessible niche, initiating armor and predator/prey races, and so on. **Each of the eight great transitions in evolutionary history** [Maynard-Smith and Szathmary, 1995], e.g. **the emergence of multi-cellular organisms, marks a new**

**coordination of constraints.** By permitting reliable cooperation instead of competition and reliable inheritance of the fruits of cooperation, the new coordinations created new complexity and opened up vast new possibilities (cf. [Sterelny, 2007]). Coordinated constraints can work their way around physical laws. For instance, while no single pump can lift water higher than 10 metres, trees lift it many times this by physically linking together (coordinating) many cellular pumps.

It is possible to obtain complex dynamics in simple systems (such as logistic reproduction). However, plausibly the only way in which the complex properties to follow can be obtained is through complex coordination of constraints of the kind neural, muscular and skeletal coordinations exemplify. These have their origins in the complex coordination of biochemical products and gradients that allow intra-cellular chemistry to support cellular maintenance. We are here far from the holonomic constraints and, as cellular regeneration shows, the no-work on constraints condition of standard analytical mechanics and deep into the domain of multiple state-dependent, interacting non-holonomic constraints.

**Intrinsically global coherence.** In analytic (Lagrangian) dynamics the globalness or otherwise of constraints is not directly considered. A holonomic constraint provides an inherently global geometrical constraint on motion in the sense of being specified everywhere, but not in the sense of demanding internal global coordination of variables. Some holonomic constraints may force component motions to be globally correlated, others will not. The same applies to non-holonomic constraints. Moreover, these can be partial rather than global, with a dynamic network of constraints structuring system dynamics, as in the cell. But if a system is to perform a global function, e.g. metabolic regeneration or amoebic chemotaxis up sugar gradients, then this will force a global organisation of its components to achieve it. Thus underlying a global functionality must be a global constraint on dynamics that ensures realisation of the function. This must be so even when this constraint is realised through a network of state-dependent, interacting non-holonomic constraints, e.g. a network of work-constraint cycles as in the cell [Kauffman, 2000]. Multiple global functionalities, characteristic of living systems, require multiple underlying global constraints, and these will normally be significantly but subtly interrelated in order to allow multiplexing (many component roles combining to realise a single function) and multitasking (the one component playing roles in realising many functions). Multiplexing and multitasking are attractive because they reduce the number of required components while increasing system functionality and adaptability, and possibly evolvability, albeit at the expense of increasing system complexity, and possibly also increasing system instability and/or rigidity.

**Order and organisation.** The constraints underlying global functionality require global organisation as distinct from global order. A high degree of orderedness means internal uniformity (e.g. a crystal) while functional organisation requires inter-articulation of distinct components (e.g. in a motor vehicle engine).

The root notion of order is that derived from algorithmic complexity theory: the orderedness of a pattern is the inverse of the length of its shortest, most compressed, complete description; hence gases, being internally random, are disordered and regular crystals, being internally uniform, are highly ordered, but neither displays any functional organisation. Sometimes complexity is taken to be measured by the inverse of algorithmic orderedness, but this leaves gases the most complex systems; in short, it ignores organisation, the key to living complexity. Machines and living things are organised because their parts are relatively unique and each part plays distinctive and essential roles in the whole. The colloquial use of ‘organisation’ is broad and vague, though its core examples are functionally organised (engines, firms, rescue teams, ...). In this essay and [Hooker-b,c, this volume], the use of ‘organisation’ is restricted to functional organisation as characterised above.

In another use of ‘order’ entirely, talk of high order features refers to features characterised by high order relations, that is, relations among relations among ... Then organisation is a particular kind of ordering in this sense, involving relatively high order relations that characterise many nestings of correlations within correlations. (Think of correlations within and between the motor, electrical management and drive chain modules of a car.) That is, an organised system displays a non-redundant global ordering relation of relatively high order, including global (sub)relations characterising global functions. For this reason organised systems must be less highly ordered than are crystals (but are obviously more highly ordered than a gas). A system’s organisational depth is measured by the degree of nesting of sub-ordering relations within its global ordering relation (cf. cells within organs within bodies within communities). Living systems are deeply organised. However, organisational depth also does not fully capture complexity.<sup>43,44</sup>

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<sup>43</sup>Because, e.g., it does not capture the distinctiveness of nested relations and the top-down relatively global constraints that modulate them. Also, in dropping the algorithmic conception, it loses ‘horizontal’ relational complexity. Gell-Mann [1994] discusses effective complexity and logical depth (see [Bennett, 1985; 1992]) and Type 2 theories (see [Marr, 1982]) as other possibilities for measuring organised complexity but neither is satisfactory for various reasons he notices — fundamentally for the above reasons. For general discussion of these issues see [Collier and Hooker, 1999, sections III and VI].

<sup>44</sup>Shalizi [2001; *et al.*, 2004] also claims to provide a measure of organisation, in this case a statistical measure. What is actually measured is called system complexity, designated ‘C’, and is, roughly, the minimum information required to specify those past system behavioural features (variables plus inputs) that make a difference to future system behaviour. (Shalizi calls these the ‘causal states’ of the system; inputs are not mentioned but without these, reflecting increasing environmental responsiveness, the effect of increasingly nested correlations might simply be more constrained behaviour and so reduced complexity.) Shalizi has a more general conception of organisation in mind — something like number of partial interdependencies or correlations — than the functional organisation characteristic of metabolism which is concerned with sets of partial correlations satisfying global constraints (so that they sustain functionalities). This latter is what this essay understands as organisation proper. For this the central issue is whether the C measure differentiates between organisation (proper) and other kinds of interdependencies among variables, e.g. those in turbulent flows. I don’t see that it is equipped to do so, since it simply counts interdependencies of all kinds. An aeroplane and a turbulent river could be judged alike in terms of numbers of required variables for behavioural prediction, but would internally be organisationally very different. Unsurprisingly (because C picks up only interdependency),

**Modularity.** A system contains a module if (and only if), to a sufficiently good approximation (e.g. to capture essential system functionality), its dynamics can be expressed as an interactive product, the dynamical product of its intra-modular dynamics and its inter-modular dynamics.<sup>45</sup> Three kinds of modularity can be distinguished, spatial or ‘horizontal’, level or ‘vertical’, and process modularity, labelled respectively S, L, and P modularity. Smodularity obtains when there is a principled division of a system into contemporaneous spatial modules such that the system dynamics is expressible as the product of the individual module dynamics and their interactions. This is how we currently design and model buildings and machines of all kinds (from homes to hotels, typewriters to television sets) and how we usually attempt to model both biological populations (the modules being the phenotypes) and often their individual members (the modules being internal organs, or cells). Lmodularity, in contradistinction, obtains when a system’s dynamics may be decomposed into the interactive product of its dynamics at different system constraint levels. This is often how business management functionally analyses a firm. (Often that organisation will express a management hierarchy and be graphically represented vertically, often realising the functional roles vertically in a building — hence the alternative ‘vertical’ label.) It is also often an important part of machine design (cf. motor vehicle electrical regulation and drive chain modules) and of the scale analysis of organisms (cells, organs, organism). Pmodularity obtains when a system’s dynamics may be decomposed into the interactive product of its process dynamics, and is characteristic of the analysis of organisms and complex machines into mechanisms, such as cellular respiration and pulp mill regulation.<sup>46</sup>

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this parallels dynamical phase space blindness to organisation, where a pendulum and a feedback oscillator are both represented by the same wave equation. C may provide a measure of interdependency, but not of organisation (proper) — and thus not of complexity either in the sense later articulated. Of course, if the behavioural data were to include sufficient data about the internal state, as it happens the pendulum and the feedback oscillator could be behaviourally distinguished even though the inherent organisational blindness persists. Exploiting that idea, if it could be assumed that sufficient internal observation would result in every distinct organisational form having its own distinct C measure, then that would suffice to at least identify the organised systems, if not order them distinctively. (Cf. the fate of Behaviourism in relation to Cognitivism, section 4.2.4 below.) Cyclical temporal interdependencies of the kinds that characterise many metabolic processes (e.g. Krebs cycling) can certainly be detected with appropriate internal observational data (using temporal autocorrelation in the data stream), and also their temporal nestings. Indeed these interdependencies will already form part of the C total if the scope of observation includes them. But disaggregating them within total C may be very difficult.

<sup>45</sup>Then all system components, at whatever level of analysis, are modules, with basic components being those taken to have no internal dynamics and fixed inter-modular dynamical interactions. This is a physicist’s definition. For an inequivalent and weaker but related computational definition in terms of network connectivity, see [Green and Leishman, this volume, ‘Encapsulation and modularity’]. The conceptions are inequivalent because interaction strength is not equivalent to network connectivity or even to information transmission densities. The dynamical conception is stronger because it can distinguish L from S and P modularity, which is difficult to do in purely network connectivity terms. As an information transmission conception the network conception is most closely related to P modularity.

<sup>46</sup>Note that each of S and L modularities define a relative, interactive conception of ‘part’. (This is clearer for the network interaction conception, see note 45.) But parts may interact strongly,

As motor vehicle design illustrates, all three modularities may be combined, at least to significant extent, in current simple engineering designs. Here S and L modularity will create the constraints to enable corresponding functions in simple, reliable ways (though in the process disabling many others). The earlier viable system movement that sprang from cybernetics and general systems theory (see Beer and others, section 2) relied on such designs. But modular processes may also cut across levels and spread throughout a system and to that extent exclude S and L modularity. Modularity of any kind reduces system complexity, by decreasing dynamical degrees of freedom, while increasing functional and possibly developmental reliability and ease of repair. Like any coordinated constraint it will in general both disable and enable and thus have a complex relationship to higher order system properties like multiplexing and multitasking, adaptability and evolvability. Nor is there any simple relationship to reduction; simplification and decomposition aid reduction but if the decomposing modularity is achieved through self-organisation (e.g. in a Bénard cell system) then it also thwarts reduction.<sup>47</sup>

**Hierarchy.** Hierarchy proper is asymmetry of level (vertical) control in a sufficiently Lmodular system. While common in machine design and as underlying principle in organism and institutional design, pure hierarchy is in fact the exception, and is rarely more than partial in living systems. A higher level constrains lower level dynamics (as a crystal lattice constrains the behaviour of its atomic constituents), will often regulate it through feedback (e.g. coherence of crystal vi-

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so neither S nor L (nor P) modularity is equivalent to an ontological part/whole relation, though on occasion they may have this effect. Likewise, none of them corresponds to a general/special (genus/species) hierarchy, though on occasion they may have this effect. (These latter distinctions may be less clear in the network conception.) Hmodularity in [Collier and Hooker, 1999] = Smodularity here.

<sup>47</sup>Modularity is one form of system composition, that is, of the relationship(s) between parts and whole. Another — aggregate composition — satisfies the condition that the whole is the simple sum of its parts. Various attempts have been made to decompose the non-aggregative systems, e.g. into nearly and minimally decomposable compositions [Simon, 1969; 1997] or component and integrative compositions [Bechtel and Richardson, 1993]. These ideas have to be applied carefully. For Simon's idea of near-decomposition, e.g., a Bénard cell system can be approximately described as a combination of separate cells, at least *while the producing conditions apply and the system is kept away from thresholds*. But move near or over a threshold and the continuing underlying global complexity of the system makes itself apparent. Again, one reading of the component/integrative distinction, e.g. by [Boogerd, *et al.*, 2005] who discusses it for cell biology, is in terms of the degree of alteration of a component's interactive capacities on entering a compositional relationship. But this applies only to sufficiently complex components like proteins (and organisms entering a culture — see section 4.1.2 below); the wider condition is simply top down constraint, corresponding to the alternative reading of the distinction, and providing a significantly different categorising of composition conditions. In sum, while there is a general intuitive sense of increasing mutual constraint from aggregative to nearly-decomposable/component to minimally-decomposable/integrative compositions, there are many different forms of mutual constraint, e.g. global constraints versus modularity, including all the collective properties discussed in this section. Whence there is no obvious simple ordering of their manifold possible compositions. The upshot is that these distinctions don't seem amenable to sharp dynamical characterisation and will not be pursued.

brations) and sometimes it will also control the lower levels in important respects (top down control, e.g. brain control of muscle). But it will also typically be true that lower level dynamics will constrain higher levels (as electron orbital dynamics constrains crystal angles), may regulate them through feedback (e.g. in catalysis of chemical reactions) and might control certain aspects of the higher level (bottom up control, e.g. indirect control of volume Hebbian learning through local NO release). And in many cases there will be no control asymmetry involved, simply mutual constraint through interaction, e.g. of oscillatory behaviour in a system of small oscillating springs connected to a common rigid, but moveable, bar. This latter interaction-only condition will be the common case among Smodular components at the same level, e.g. among cells of the same organ. Whenever there is a control asymmetry we shall speak of hierarchy relationships, with the direction of the hierarchy being the direction of control asymmetry.<sup>48</sup>

**Path-dependence and historicity.** Path-dependence occurs whenever there is positive amplification, for then initially nearby dynamical trajectories subsequently diverge as a function of small differences in their initial conditions, so the path taken depends on precisely where the first step began. A notable sub-class of path-dependencies are those where, once begun, development along a certain path itself becomes increasingly entrenched. This applies where, e.g., an initial fluctuation is amplified and entrenched, especially where that entrenchment involves a bifurcation that reinforces the irreversibility of the development. Examples include a particular impurity site of first freezing or of rolling boiling, a first genetic mutation that yields a distinctive kind of adaptive advantage or a first oil discovery or shop in a new suburb that transforms a local economy. These cases exhibit a clear sense of historical possibilities exploited, and correlatively of others foregone, and their resulting paths are often said to ‘fix’ their initial historical conditions.<sup>49</sup> By contrast, for stable systems in an attractor basin there is no overall path-dependence since the same outcome occurs (capture by the attractor) for all beginning points (initial conditions).

**Constraint duality and super-system formation.** Coordinated constraints that enable while disabling, e.g. the disabling movement constraints imposed by a skeleton and its enabling of locomotion and leverage, exhibit general constraint duality. The notion has a specific application to forming systems into

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<sup>48</sup>Cf. [Eldredge, 1985; Nicolis, 1986; Pattee, 1973; Salthe, 1985; 1989]. Dyke’s [1988] usage is confined to the rare special case where constraint is one-way only. Commonly among living and human engineered systems a hierarchy is specified by assembling cohesive, Lmodular combinations of Smodular components, e.g. building organs from cells and bodies from organs, cf. [Ravasz, *et al.*, 2002]. But it is possible to have at least dynamically distributed feedback regulation that doesn’t require S or L modularity, e.g. the distributed rate dependency phase separation of Belusov-Zhabotinsky chemical reaction structures.

<sup>49</sup>However, it would stretch the notion of *physical* constraint to vacuity to call these initial conditions path constraints, because there is no cohesive force involved that grounds the constraint.

super-systems through mutual interaction. System constraints may contribute to enabling super-system capacities, for example the role of mitochondria in eukaryote energy production. Conversely, super-system constraints may free up system constraints, for example wherever multi-cellular capacities permit member cells to specialise. But it has a wider application in considering social community formation. We can gain a crude measure of the importance of socialisation to a species by considering the ratio of *usable* individual parametric plasticity (i.e. adaptiveness) between isolate and communal states. For simpler creatures of lesser neural capacities and more rigid social organisation, such as the insects, the relation is typically negative, individual capacities are sacrificed to communal cohesion and function. Oppositely, humans increase their coherently usable individual capacities enormously through collective culture, even while contributing to communal capacities. Unless we humans have a sophisticated, high quality cultural environment in which to develop there will be vast reaches of our somatic, especially neural, organisational space that we cannot use because it is not accessible to us. Thus for humans there is a positive relationship between individual and communal capacities. Coupled constructively, each enables the other, and together they largely (not wholly!) dominate those coupled competitively. (We can speculatively picture this effect increasing through the mammalian line as brain size, intense socialisation and intentional action increase together.) This makes all the difference to the power of culture, to its significance in adaptive evolution, and to the intricacy and globalness of its organised dynamics (cf. Section 4.1.2 below).

**Coordinated spatial and temporal differentiation with functional organisation.** Multiplexed, multitasked functions cannot all be realised simultaneously at every location, the resulting interference would render reliable performance impossible. It is necessary then to distribute the realising dynamical activities spatially and temporally so that each local area over each process cycle is restricted to a coherent set of concurrent activities. Moreover, these distributions have to be subtly organised so that each function is realised at convenient locations and times for receiving its inputs and also useful locations and times to contribute its outputs. Similarly, cellular metabolism requires a group of closed self-reproducing processes to recreate the constraints for each process from the products of other processes — Kauffman’s [2000] work-constraint cycles — and this too requires subtle spatial and temporal differentiation to achieve reliability and effectiveness.

**Multi-level and multi-order functional organisation.** Metabolism, for example, refers to the organised network of biochemical interactions that convert input matter and negentropy (food and water) into usable forms and direct their flows to various parts of the body as required, for example for cellular respiration. The individual biochemical reactions are largely known. However it remains a challenge to characterise multi-level processes like respiration, comprising processes from intra-cellular Krebs Cycles to somatic cardio-vascular provision of oxygen and removal of carbon dioxide. These processes must be made coherent across the



entire body for respiration to work. The overall process of respiration is *multi-level*: involving sub-cellular to organism coordination, *multi-dimensional/plexed*: involving organised interactions among many body parameters, *multi-modal/tasked*: involved in many different bodily modes of operation (motor, cognition, stress, etc.), e.g. the cardio-vascular system simultaneously transports resources (oxygen etc.), wastes (carbon dioxide etc.), regulatory hormones, and so on, and *multi-phasic* (asynchronous and non-stationary): respiratory processes occur on many different timescales, with local parameters constantly changing functions of temporary activity while more global respiratory parameters are functions of the longer term developmental and subsequent functional history of the organism. In this conception, global coherence is a result of internal regulation at various functional orders and scales.

**Autonomy.** Autonomy is a particular global functional coherence. It is the internally organised capacity to acquire ordered free energy from the environment and direct it to replenish dissipated cellular structures, repair or avoid damage, and to actively regulate the directing organisation so as to sustain the very processes that accomplish these tasks. There are two broad cyclic processes involved, internal metabolic interaction and external environmental interaction, and these need to be coordinated: the environmental interaction cycle needs to deliver energy and material components to the organism in a usable form and at the times and locations the metabolism requires to complete its regeneration cycles. At the same time the metabolic cycle needs to include a capacity to regulate the metabolic organisation so that both the external interactive capacity and its own regenerative capacity are sustained. (E.g. a cell can alter an internal chemical balance or gradient by ionic intake or expulsion and respond to environmental deficiency by tumbling.) This organisational regulation needs to be coordinated with the basic regenerative and interaction cycles; it may be fused with the regenerative process. The presence of these two thus synchronised cyclic processes resulting in system regeneration is the broadest functional sense of what is meant by a system's being autonomous.

Though the detail, especially the dynamical boundaries, vary in graded ways across living organisms, this autonomy requirement picks out all and only living individuals — from cells, to multicellular organisms to various multi-organism communities, including many suitably organised business firms, cities and nations. But because only autonomous systems have their functions serve their own physical regeneration, in turn supporting their functioning (they are 'recursively self-maintenant' [Bickhard, 1993]), they represent a distinctively new category of complex system organisation. (Though all living systems are ipso facto non-linear, irreversible, open, self-organising, globally constrained, etc. systems, non-living systems may also manifest one or more of these properties, cf. [Fox Keller, 2007], but not autonomy.) For the same reason, in all autonomous systems the locus of living process regulation lies more wholly within them than in their environment — hence it provides a root sense of autonomy that supports the tra-

ditional sense.<sup>50</sup> Birds organise twigs to make nests, but twigs themselves have no tendency to organise nests or birds. Entities with a distinctive wholeness, individuality and perspective in the world, whose activities are willful, anticipative, deliberate, adaptive and normatively self-evaluated, are properly treated as genuine agents; autonomous systems are inherently all of those things (section 4.1.1 below).

**Adaptation, adaptiveness and learning.** An organism is adapted when it possesses an autonomy-satisfying set of traits in its life-environment. Conversely, an organism's ecological niche is comprised of the range of life-environments for which its traits provide satisfaction of autonomy. An organism's adaptiveness is its capacity to alter its specific traits in mutually coordinated ways so as to adapt to, that is, satisfy autonomy in, different life-environments. Humans can run as well as stand still and this enlarges the range of prey they can catch, predators and natural disasters they can evade, and social commerce they can sustain. Shifting from standing still to running involves coordinated changes in physiological processes, sensori-motor feedback/forward foci, etc. The set of coordinated trait variability ranges consistent with autonomy-satisfaction comprises an organism's adaptive envelope. An organism's adaptability, adaptive potential, or adaptiveness is some measure of this set. Learning, understood most generally, is the application of adaptability to develop adaptations. Ecologies and evolving populations learn only in this broadest sense, through changes to the internal compositions of their populations. Understood more narrowly, learning is the broad process manifest through internal sensory, memory and motor regulation, that is, through neurally modulated behaviour. Organisms learn in the narrower sense, which generally offers more powerful, but less broadly applicable, problem-solving capacities. Broad and narrow learning processes can be complexly combined and it can be instructive to inquire how various community groups, from colonies and flocks to human business firms, cities and nations, learn.<sup>51</sup>

To these properties of complex systems is added two further properties that might equally be said to characterise our study of them, though here they are considered as properties of the systems themselves.

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<sup>50</sup>On autonomy and self-maintenance see further section 4.1.1 below and [Bickhard, 1993; 2000b; Christensen and Hooker, 2000a; 2002; Moreno and Ruiz-Mirazo, 1999; Moreno and Lasa, 2003; Ruiz-Mirazo and Moreno, 2004; Moreno, 2007; Moreno *et al.*, this volume], and references. This includes reference to the root preceding tradition [Varela, *et al.*, 1974; Varela 1979], now a main alternative, autopoiesis [Maturana and Varela 1980; Maturana 1981]. Self-governance lies at the core of our commonsense conception of autonomy. However, we are most familiar with the idea of autonomy as applied to persons and political governance. But these are sophisticated notions applied to sophisticated systems whose trappings may distract from fundamentals. We need to return to basic principles operating in all living systems to construct a naturalist notion that will 'grade up' across the evolutionary sequence to our sophisticated concept.

<sup>51</sup>For a more detailed articulation of a basic functional organisation underlying cognition, including anticipation, normative evaluation, self-direction and self-directed anticipative learning, see section 4.1.3 below and e.g. [Christensen and Hooker, 2000a; 2000b; Farrell and Hooker, 2007a; 2007b; 2009; Hooker 2009b; Hooker and Skewes, 2009].

**Model centredness and model specificity/model plurality.** Complex systems of the foregoing kinds are typically characterised by dynamical equations that lack analytical solutions. Thus it is necessary to explore their dynamics through computational simulation. This places computational modelling at the centre of their scientific investigation in a strong manner. Model centredness refers to this feature. It highlights the unique contribution of computers to cognition (all its other uses being pragmatic, if often valuable). Since all computer modelling is finite, all quantitative models have inherent uncertainties in them, e.g. ‘rounding off’ errors. Further, mathematical science contains many non-computable mathematical functions, that is, functions where information crucial to identifying it is lost with any degree of finite approximation.<sup>52</sup> This provides a practically ameliorable, but ultimately ineliminable, basis for uncertainty about system state whenever the system dynamics involves positive amplification. Moreover, different implementations or simulations of a given theoretical model can exist, e.g. employing different machine architectures and programming languages, and these need not be equivalent in expressive power, accessibility or performance (see, e.g., [Axelrod, 1997]). These variabilities represent a further source of uncertainty in modelling. They can be removed by demonstrating that the relevant outcomes are independent of implementation, or by restricting data to what is robust across implementations (or by requiring that there is available a special defence of a particular simulation), but this is seldom done, not least because the list of simulations to be checked is indeterminate. Uncertainties eventually translate into errors, if they are ignored or arbitrarily resolved (e.g. by rounding off). Thus though computational numerical approximation represents a huge expansion of our capacity to know complex dynamics, it also represents a selective, but important, diminution in our knowledge capacity. On the other hand, the centrality of computational modelling provides the platform for making new complexes of modelling methods, e.g. use of evolutionary game theory and genetic algorithms. The full extent of these supported methods needs exploration.

Since it is frequently impossible to model the full complexity of systems, it is necessary to choose partial parametric models aimed at capturing the basis of some class of phenomena. Model specificity refers to the capacity to select parameter values so as to specialize the model to the characterization of some unique individual and/or situation. Conversely, model plurality refers to the capacity to capture the characterization of a plurality of individuals/ situations within its parameter ranges. These features are respectively the basis for deducing feature ranges in

<sup>52</sup>See e.g. [PourEl and Richards, 1989; Shipman, 1992] Many superposition or ‘wave’ phenomena (classical and quantum) are of this kind where wavelet information at indefinitely small scales is important to identifying the whole function. Here a mathematical function is a many:one map from a domain to a range, hence unique on the range. One distinctive merit of the proposal to model natural (e.g. biological) functions as input/output maps is that this relates them directly to mathematical functions and hence, via modelling, to dynamical maps and so to biochemical processes. For some instructive exploration of computation in science see Humphries 2004, the *Proceedings, Workshop on Physics and Computation*, IEEE, 1992 generally and [http://en.wikipedia.org/wiki/Digital\\_physics](http://en.wikipedia.org/wiki/Digital_physics), [http://wapedia.mobi/en/Church-Turing\\_thesis?t=9](http://wapedia.mobi/en/Church-Turing_thesis?t=9).

individuals from more broadly characterised systems, e.g. populations, and for formulating valid generalisations across sets of individuals, e.g. across populations. And this in turn is the basis for condition-dependent laws that are the norm in all such complex systems domains.

**Condition-dependent laws.** Compared to the universal, invariant laws of physics, the local idiosyncratic behavioural patterns exhibited by many complex systems don't seem to qualify as laws. Of course biology and cognate sciences dealing with complex systems do use universal laws in constructing their models, e.g. if the elemental laws of chemistry did not operate the same everywhere, bio-chemistry and hence biology would be much harder than it already is. Even so, the complication arises from the fact that the nomic invariance largely occurs at the ion-ion interaction level but how n-body, k-component ion systems operate is often a sensitive function of the initial and constraint conditions, especially organisational conditions, obtaining. The bio-chemistry of carbon-hydrogen chains provides eloquent illustrations, for instance where folding history can alter subsequent interaction dynamics (e.g. via which binding sites are active). That is why no simple set of laws can be deduced in advance. However, the phenomenon is universal within science. Consider that, e.g., electric circuit dynamics is the outcome of many universally lawful component interactions, but it is the material circuit conditions that determine the outcome circuit law, e.g. whether it is oscillation, exponential decay or other. These circuit-design-dependent dynamics are properly considered law-like despite arising from specific material conditions (see any engineering text on oscillators or circuit design).

Moreover the point extends to laws conditioned on self-organisation, a distinctively complex systems circumstance. Pertinently, self-organisation precisely occurs because of the sensitivity of dynamical form to dynamical initial and constraint conditions (see above). But since self-organisation involves a new dynamical form, it is reasonable to say that it obeys new dynamical laws characteristic of that form. For instance, consider this condition: a cooling mold of liquid iron in contact with a heat reservoir of lower temperature. It leads to new emergent laws — rigid body (not fluid) dynamics, crystalline (not fluid) conduction of electricity, heat and sound. The universality requirement drops out.<sup>53</sup> Then we are free to see biology and cognate domains as replete with real laws, just as is physics. It is at most that they will be condition-dependent on highly intricate, perhaps idiosyncratic, and typically organisational, conditions.<sup>54</sup> (They will be 'special', as some philosophers say.) Also, often their form will be hard to predict but, so far at least, this distinguishes them from the situation in physics by at most a matter

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<sup>53</sup>In any case, the requirement of universality, that is, to be specified independently of any initial and constraint conditions, is a conceit of fundamental physics, and perhaps ultimately not true there either considering that even fundamental laws evidently changed form as the big bang cosmos cooled.

<sup>54</sup>See [Polyani, 1968] which offers an early diagnosis of the condition-dependence of laws for biological organisms, and argues that their peculiar conditions (essentially autonomy, see above) makes reduction impossible.

of degree, not kind.<sup>55</sup>

This discussion provides a rich set of concepts and principles for characterising complex systems. For instance, Mayr [2004] provides a list of features distinctively characterizing biological systems and which he claims sets biology apart from other natural sciences: metabolism, regeneration, growth, replication, evolution, regulation, teleology (both developmental and behavioural). However, comparing his list with that of complex systems features above it is pretty clear that, at least in principle, complex systems provide resources for modelling, and hence explaining, each of them and molecular, systems and synthetic biology are between them well on the way to doing so. Again, the Santa Fe Institute was an early pioneer, dedicated to the explicit study of complex systems, its inaugural volume [Pines, 1985] providing a first cross-disciplinary preview of their diverse applicability. Its orientation then was summed up by Gell-man: the study of n-body dynamics of simple rules that generate complex behaviour, exhibited through such paradigm technical tools as cellular automata and Boolean nets. Today we can see that, while these systems comprise a distinctive group of typically counter-intuitive cases, and constitute rich worlds of phenomena<sup>56</sup>, we now include within the scope of complexity all the dynamical behaviours associated with all of the complex systems features just reviewed. From this perspective the present volume is a characteristic successor to that early volume. The richness of its modelling and methodological and epistemological considerations reflect the hugely expanded conception of complex systems and vastly increased breadth and depth of their impact across all the sciences.

Despite the richness there are certainly further notions that might have been included. Some are constituted in more fundamental notions and are left to exposition elsewhere. Synergy [Haken, 1983; 1993], e.g., though of interest, results from some combination of positive feedback and coordinated constraints (in some cases with constraints and negative feedback to stabilise it). However, two fundamental notions concerning the basic metaphysics of complex systems are perhaps surprisingly absent: identity and complexity. They are absent because, like emergence and self-organisation, they are labels for a ‘swamp’ of diverse, and sometimes confused, ideas; e.g. Edmonds lists nearly 400 complexity references with great diversity among them, and that list is only partial.<sup>57</sup> Moreover, unlike emergence and self-organisation, there seems relatively little of a science-based, dynamical

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<sup>55</sup>See further section 4.2.2 below. Note that, although they may seem to be closely related or even the same thing, condition-dependent laws are really the opposite of *ceteris paribus* laws [Earman, *et al.*, 2002]. The latter state that some reference condition occurs in standard circumstances, the exceptions picked up, otherwise unidentified, by the *ceteris paribus* collector. Sometimes this can be practically useful, but unless the exceptions are due to irresolvable noise, it represents a halt to scientific progress. Whereas the point of condition-dependence is to decompose the exceptions into differing conditions that change the law in systematic ways, neither random nor ignorable but at the heart of understanding the dynamics of the systems involved.

<sup>56</sup>Even sufficient for Wolfram to claim a ‘new science’ for cellular automata simulations, see [Wolfram, 2002].

<sup>57</sup>See <http://bruce.edmonds.name/combib/>, cf. [Bishop, this volume, section 2.5] and references.

nature that can sensibly be said about structuring these concepts.

Some remarks on identity are found in [Hooker-b, this volume, section 6.1B], while [Cumming and Collier, 2009] and [Bishop, this volume, section 2.7] show the difficulties involved in trying to develop more detailed systems identity criteria. As for the notion of complexity, the collection of concepts and principles gathered above should suffice to indicate the diversity and complexity of what needs to be covered — this is why its discussion was postponed until now. The same collection also suffices to show the insufficiency of any of the commoner simple ideas of complexity — number of degrees of freedom (component numbers), algorithmic incompressibility, levels, ... — to capture the notion by themselves. To approach its characterisation, first omit all epistemic notions as ultimately derivative considerations, e.g. those appealing to intelligibility and surprise, and all ‘external’ notions like controllability. Then at the least complexity has, I suggest, five quasi-independent dimensions to it: cardinality (component numbers), non-linearity (of interaction dynamics), disorderedness (algorithmic incompressibility), nested organisation (organisational depth) and global organisation. While I agree that these ‘dimensions’ are not fully mutually independent, it is also true that some are partially opposed and I do not know how to systematically characterise their inter- and counter- dependencies so as to produce a clearer, reduced dimensional analysis. I do not know of any one measure that can capture all these dimensions and I do not think anything less rich is adequate to the forms complexity can take.

In particular, trying to simplify the problem by leaving out globally organised constraints, when they are central to functional characterisation, much less by ignoring organisation entirely, is to aim at capturing a physics-centred class of cases at the expense of missing much of the special importance and challenge of complexity. Conversely, leaving out the forms of non-linearity involved may still allow structure and patterns to be discussed, e.g. bifurcation thresholds and attractors, but in omitting their quantitative character and distribution it misses understanding the roles and complications of noise, resilience and the like. Though aspects of this complex concept have large technical literatures associated with them, I suspect that at the present time the foregoing is the best that can be managed concerning characterising complexity in its largest meaning.

There remains then to tackle the question of what a science using such systems models and studying corresponding systems might be like in its foundations, philosophy and practice. Just this is of course the point of this volume. In [Hooker-b, this volume] some of the more general themes will be picked out. Meanwhile, there follow some particular topics that should ideally have found a place among the essays but did not do so.

## 4 SPECIAL TOPICS

### 4.1 *Three interrelated complex systems ideas that challenge orthodoxies*

Each of the complex systems ideas to follow is in its infancy. The first, autonomy, is sufficiently well developed to understand its significance, but its domain, biology and bio-sociality/robotics, has yet to really feel its impact. The second, cultural dynamics, has barely been identified and has yet to receive sustained exploration. The third, science dynamics, has a range of recognised models offering various expressions of it, but arguably these are all preliminary models on the way to a more mature expression. Nonetheless, these ideas represent the application of complex systems to three of the most basic features of human life, our constitution, culture and cognition. As such, they are worth exploring in themselves, to help correct the relative neglect of these domains within complex systems development thus far, and to expand the range of our understanding of what the introduction of complex systems means for scientific understanding, the theme of this book.

#### 4.1.1 *Autonomy*

The first of these ideas is autonomy, the coordination and regulation of the internal metabolic interaction cycle and the external environmental interaction cycle so that the latter delivers in timely manner to the former the resources it requires to regenerate the organism (section 3). This idea, which is uniquely tied to complex organised systems, has manifold significances for science, of which four will be briefly reprised here.

The *first* was noted in section 3: it permits the demarcation of living systems. It is by no means the only approach to demarcating life and readers are encouraged to consider others. (See [Bedau, 2007] for a review of approaches.<sup>58</sup>) However it is deeply related to the unique organisation of living systems (cf. [Ruiz-Mirazo, *et al.*, 2004]), while not tied too closely to their chemical detail. And it uniquely picks out the living systems from within the wider domain of complex, organised, non-linear, dissipative (entropy increasing) and irreversible, chemical and biological systems. Whence it provides an unbiased, operational criterion of life hitherto missing and especially needed in exo-biology, where physical criteria (typically those above) are too wide and psychological criteria (intelligent, etc.) are too narrow. Moreover, though the detail, especially the dynamical boundaries, vary in graded ways across different living systems, autonomy has the advantage of not being confined to cellular organisms but extends to suitably organised social groups, where it picks out living individuals, from cells to multicellular organisms to various (by no means all) multi-organism communities, including many business firms, cities

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<sup>58</sup>An informal, less structured but still useful starting review is <http://home.planet.nl/~gkorthof/korthof66.htm>.

and nations.<sup>59</sup> Many otherwise plausible-looking systems are not autonomous: all viruses, candles and hurricanes and the like, most or all ecologies, most social institutions (community sports, cafes, markets, ...), many business firms, and so on. These all lack sufficient organisational capacity to regulate themselves.<sup>60</sup> In consequence, Smith's hidden hand of the market has at best a weak existence (there is but a relatively scattered set of feedback loops, though some of them may be of great importance, and more are being added), as does Lovelock's Gaia for similar reasons. But at least we have a principled basis for analysing the vulnerabilities of these systems and hence for shaping our management policies toward them. Similarly, business firms too can benefit from a systematic understanding of their organisational deficiencies as viable enterprises, as can many other social institutions (though not all need to be so persistently focussed on survival as autonomy forces).

Although all this is so, there remains an important issue concerning precisely how to demarcate autonomous systems. The cell, but not the candle, regenerates itself (metabolism), including its own metabolic organisation to do this, and self-regulates that organisation to aid its continued viability (note 60). If complete closure in regeneration and regulation held (autopoiesis), this would provide a crisp demarcation of living systems. But the essence of the evolution of multi-cellular creatures has been the enlarging of their interactive capacities while (modestly) opening up both the closure of their metabolism, e.g. by amino acid imports in humans, and the flexibility of the regulatory closure of regeneration, e.g. by

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<sup>59</sup>The close and older cousin of autonomy, autopoiesis, provides a similar demarcation. It will also share the other significances attributed to autonomy below. However because of its closure emphasis, as opposed to the interactive openness of autonomy (see below), the two will part company, somewhat over multi-cellular organisms, but especially over social organisations where autopoiesis finds much less application. Also, the formal closure of the planet could make it appear lifelike under autopoiesis, whereas its self-regulatory capacity seems too weak. I consider this another reason to favour autonomy over autopoiesis.

<sup>60</sup>A simple but useful comparison is that between a candle flame and a cell [Maynard-Smith, 1986]. A candle flame pre-heats its wax, permitting it to rise into the wick, and creates convection air currents delivering fresh oxygen, thereby supporting the burning process (flame). So it is, as Bickhard [1993] says, partially self-maintaining and (passively) recursively self-maintaining in these respects (that is, the same processes that maintain the flame thereby maintain the capacity to maintain the flame). In doing this a candle flame creates and sustains a thermodynamic asymmetry between itself and its environment, based in a (minimal) organisational asymmetry. This is essential for its continued existence as a far-from-equilibrium [ffe] thermodynamic system. The stationary cell does all this, but it also has two further organisational properties, (i) reproductive closure — it succeeds in regenerating all aspects of itself (metabolism), including its own metabolic organisation to do this, and (ii) it self-regulates that organisation to aid its continued viability, that is, it responds to distortions in its functioning with corrective measures, e.g. altering a chemical balance or gradient by ionic intake or expulsion, altering environment through tumbling. We might say that it is actively self-maintaining of its self-maintaining organisation (as opposed to the candle's passivity in this respect). It is these properties, not mastery of the environment per se, that mark off the autonomous systems. They create a distinctive organisational asymmetry between the cell and its environment that results in the locus of cellular regulation lying within the cell and not in its environment. But it is its interactive relations with the environment, essential to its ffe nature, that are the focus of its evolutionary development.



distorting metabolism to support interaction (extreme: burning internal organs to support marathon running). In the right circumstances, openness of these kinds contributes to fitness. (And note that we take in the amino acids despite having a regulatory membrane — skin; but a multi-cellular skin is more open than a cell membrane.) Indeed, interaction capacity in the form of medical science can now intervene throughout metabolism, export manufacture of body parts (from knees to hearts) to industry, and so on.<sup>61</sup> But this removes the crispness to the autonomy boundary. Every export of manufacture to the environment represents a loss of regulatory organisation to the system, at least of regeneration, but of organisation as well in cases like heart pacemakers. How much openness of cyclic processes can be tolerated before autonomy fails, before so much manufacture, and/or so much regulation of metabolic organisation, is exported to the environment that the locus of organisational regulation shifts from the organism to its environment?<sup>62</sup>

These are typical of boundary problems for open complex adaptive systems. They make autonomy analysis of social entities like firms, cities and nations particularly complex because the boundaries themselves have been rendered still more diffuse in favour of increased regulation of flow organisation. Future robotics, now that embodied design has begun at last to take hold (cf. below, [Barandiaran and Moreno, 2008]), will also provide challenging cases. Meanwhile, consider the following, partially related formulas (I) ‘their thermodynamic asymmetry with the environment is explained by regulatory loci that are more within the system than in the system environment’ and (II) ‘actively regulates its regenerative organisation’. Used to determine the scope of autonomy, either of these formulas, a fortiori their conjunction, will suffice to clearly exclude the candle, hurricane, viruses and the like but clearly include organisms, and leave open the future border cases in robotics that are sure to come. I would prefer to have available more penetrat-

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<sup>61</sup>At this point a difference between autopoiesis and autonomy highlights the subtleties at issue. (Autopoiesis is Maturana and Varela’s term [1980; cf. Varela, *et al.*, 1974], the pioneers of this analysis, although they have also used ‘autonomy’ [Varela, 1979]. So in what follows please read ‘autonomy’ as the dual loop coherence described in section 3.) Maturana and Varela emphasise closure as their key distinguishing feature of autopoiesis; to put it crudely we might say that autopoiesis = complete reproductive closure + complete self-regulatory closure of reproductive closure. And they are impressed by the existence of the cell membrane as the regulatory device for maintaining the locus of regulation within the cell. This conception has the advantage that it is relatively sharply defined. [Rosen, 1991], e.g., even thought that he had shown that no such system had computable models, but [Mossio *et al.*, 2009; Stewart and Mossio, 2007] claims to have a counter-example. Pattee [1995; cf. 1996] thought that closure entailed semantics because it entailed self-reading’, and was the only way to create semantic content, hence concluded that the genome was the origin of meaning content in biology. But the burden of the preceding text is that this orientation is neither accurate nor captures the focus of evolutionary development. See also note 69 and text.

<sup>62</sup>The complexity involved in answering is increased by the fact that we cannot do this analysis organism by organism. First, medical capacity spreads the environmental regulatory capacity among all of us, it makes no sense to ask how much environmental regulatory capacity a particular human distinctively relies on. (This would already be true as soon as humans collectively impacted the spread of plants with the missing 9 amino acids — whether they knew it or not.) Second, it would already deny autonomy to each of our cells, since each relies on specialised cells in other organs to manufacture and deliver many of their required inputs.

ing and crisp characterisations of the relevant distinctions. I can't even be sure I've correctly characterised the problem or done justice to the alternative. I do think that these issues go to the heart of understanding biological (and social) organisation.

A *second* significance is that it introduces organisation as fundamental to life. Finite systems sustaining dynamical equilibria far-from-(static)-equilibrium must do so by irreversibly taking in ordered or low entropy energy and material components from their environment and exporting to it material components carrying dissipated, less ordered or higher entropy energy. These open systems must be organised: by the Morowitz theorem [Morowitz, 1978], they must have at least one, and typically will have many, closed-loop processes running within them. This result applies whether or not the systems are living, as earth's weather and its organisms illustrate. However, comparing living systems to reversible equilibrium, so also inanimate, systems highlights the distinctive character of living interactive organisation:

<b>Comparative System Order</b>			
<i>Property</i>	<i>System Kind</i>		
	GAS	CRYSTAL	CELL
Internal bonds	None	Rigid, passive	Adaptive, active
Directive ordering*	Very weak, simple	Very strong, simple	Moderate, very complex
Constraints	None	Local	Global
Organisation	None	None	Very high

\* Directive ordering is spatio-temporally selective energy flow

Moreover, much or all of living organisation is to support organism functionality and it is thus organisation under these global functionality constraints.

Such global organisational requirements can in fact be met only by complex congeries of mechanisms subtly coordinated in both space and time and possibly emergent.<sup>63</sup> Whence autonomy and its realising organisation pose important challenges to scientific understanding. Science has as yet only weak tools for studying organisation and equally weak tools for studying global constraints, especially spatio-temporally extended global constraints like autonomy. Rosen argued that living systems were not mechanical, that they could not be reduced to congeries of mechanisms of the sorts found in machines ([Rosen, 1985a; 1985b; 1991], cf. note

<sup>63</sup>As self-regenerating systems, internally their cyclic processes must contribute to re-creating each other, that is, each process must partially regenerate the material constraints for themselves and/or others to work, requiring a highly organised web of cyclic process-constraint interdependencies — what [Kauffman, 2000] calls work-constraint cycles. Multi-cellular organisms perform the same overall tasks as do uni-cellular ones, only with an expanded range of self-regulatory capacities, for both internal interaction (e.g. the cardio-vascular resource delivery and waste removal system) and external interaction (e.g. neurally regulated sensory and neuro-muscular motor systems, etc.), to match their expanded regenerative requirements. They are models of self-regulation, including of active self-maintenance of their self-maintenance capacities.

61). The gist of his argument is that their functions, being required to include reproducing the system, are both cause and effect of the system (cf. [Coffman, this volume; Moreno, *et al.*, this volume]) and that this precluded their being machines. That is, the holistic, organisational features like autonomy that are central to being alive cannot be captured by analysis into machine mechanisms, which have a function but one provided externally and which does not contribute to the generation of the mechanism components. Rosen argued that these limitations, largely unrecognised and unexamined, represented a powerful limitation on the development of biological science, and ultimately on all other sciences and that meeting them would ultimately require transforming all science, from physics on.<sup>64</sup>

There is, as just seen, some point to Rosen's line of objection. Metabolic regeneration is central, does exhibit autonomous organisation and currently cannot be adequately modelled dynamically. However, it is also not magic, it has a dynamical basis in biochemistry. The problem is at least that the science of spatio-temporally organised biochemical systems is still developing. Since new tools to understand at least complex spatio-temporal organisation of interaction are currently being developed (e.g. using cellular automata models), the current lacunae might best be temporarily recognised as so many methodological challenges rather than a priori demonstrations of the separation of biology from natural science (cf. [Bechtel, 2007]). Even so, constructing workable biochemical models of cells, even very elementary cells, is difficult (note 67), and there is no inherent capacity in any of these tools to represent either organisation per se or globalness of constraints, nor therefore the roles of contingent coordinating enabling constraints, cf. [Hooker-c, this volume; Juarrero 2002; Van Orden *et al.*, this volume]. Accommodating these features might indeed force fundamental changes on the formulation of dynamics, as Rosen supposed, or it may simply be that, as the capacity to model spatio-temporal organisation grows, more and powerful such tools will sufficiently alleviate these problems.<sup>65</sup>

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<sup>64</sup>Their final version [Rosen, 1991] is couched in an arcane modelling language, and the ground has shifted somewhat from the earlier focus on systems that have internal predictive/anticipative models of themselves and their environment - see the instructive essay [Pattee, 2007] and for Pattee's version see [Pattee, 1993].

<sup>65</sup>See further [Hooker-c, this volume], note 18 and text. It should also be noted that this issue is quite distinct from that of whether and how autonomy might have evolved. Indeed, Rosen considered that life could persist without evolution but not vice versa. It seems right that autonomous systems may persist without evolving, just more precariously and so less probably, and that models of genetic algorithms do not specifically require autonomous systems. In practice, improbable miracles aside, it is hard to see how the development of complex life forms could have proceeded except through some such mechanism as evolution. Finally, how this bears on the generation of autonomy in systems is a further issue. It may well be that autonomy is realisable in many different ways, may contain components that can interrelate in many different ways and may partially or wholly self-organise under many circumstances (e.g. hydrophilic/hydrophobic lipid membranes evidently self-organise blastula), all of which, and given only that, would make an evolutionary explanation more probable (though not necessarily easy). Alternatively, it may turn out that autonomy imposes very precise requirements on at least some biochemical relationships, in the sense that none of the preceding apply to them, making an evolutionary explanation,

Dually, the challenge posed to practical construction and regulation/ control in biology and robotics is equally deep because, if the account of autonomy (and of autonomy-based cognition) is even roughly correct, it provides a set of organisational requirements for this task that will prove far from simple to meet. For instance, despite using the label ‘autonomous agent’, there are at present no truly autonomous robots in this organisational sense. Robotics uses a very limited formal notion of autonomy (something like invariant dynamical form) and limited performance criteria (typically confined to a single task) and an equally limited satisfaction method. There has recently emerged an embodied functionality movement within robotics (see e.g. [Nolfi, this volume; Pfeiffer and Bongard, 2007]) where cognitive organisation is strongly shaped by the dynamics of body and environment, in ways that you would expect from an autonomy, interactive perspective. This represents a vast improvement over the computer-in-a-machine approach that had previously dominated. However it is as yet very far from even incorporating evaluative signals representing the body coherence of robots, let alone the complexity required for self-regeneration and the capacity for fluid management of multi-dimensional environmental and internal interaction processes in relation to that.<sup>66</sup> There is an associated need to bring work on self-assembling, self-repairing robots into relation with attempts to develop artificial autonomous systems, where modelling even very elementary cells that are dynamically stable and thermodynamically coherent is proving difficult.<sup>67</sup>

A *third* significance of autonomy is that it provides a naturalistic grounding for agency. Entities with a distinctive wholeness, individuality and perspective in the world, whose activities are willful, anticipative, deliberate, adaptive and normatively self-evaluated, are properly treated as genuine agents. Autonomous systems are inherently all of those things [Hooker and Skewes, 2009].

*Self-regulation.* Autonomous systems are strongly self-regulated in both their internal and external interaction, making themselves the distinctive primary locus of their regulation. And because the self-regulation is in service of maintaining an internally coherent whole, they have a distinct, individual reference point for their activity that provides them a distinctive perspective on the world.

*Normative self-evaluation.* Autonomous self-regeneration constitutes the funda-

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given only that, less probable (cf. [Behe, 2000]). But (*pace* Behe) to know how unconditionally (or anyway less conditionally) probable or improbable an evolutionary history might be we first have to know a great deal about the natural production and organisation of relevant bio-molecules in the circumstances obtaining at the time, knowledge that is still in its infancy.

<sup>66</sup>Cf. [Christensen and Hooker, 2002; 2004] and notes 50, 51 references. While studies such as that by [Nolfi, this volume] have made progress on the fluid management of environmental interaction, these are still primitive devices when it comes to management of activity in relation to norm-derived goals. The problem in artificial life is still further from solution, since formal reproduction is not regenerative and is not the core of metabolism and thus metabolism-based action norms. See also [Moreno and Ruiz-Mirazo, 1999; Moreno, *et al.*, this volume].

<sup>67</sup>For self-assembling/repairing robots see e.g. [Groß and Dorigo, 2007; 2008] and <http://www.swarmanoid.org/index.php> and for protocell investigation see e.g. [Gánti, 2003; Ruiz-Mirazo and Moreno, 2004; Szathmary, 2005; Barandiaran and Ruiz-Mirazo, 2008], <http://www.ees.lanl.gov/protocells>, and references.

mental basis for normative evaluation because it is the sine qua non and reference point for all else. Autonomy is the condition against which the outcomes of system processes are measured for success or failure. In single cells the measurement is simply continued existence or not. Multicellular systems have developed many internal, partial and indirect surrogate indicators for autonomy satisfaction and its impending violation, often based around closure conditions for their important sub-processes, e.g. hunger (impending violation) and food satiation (satisfaction). It is these specific surrogate signals (cf. also thirst/fluid satiation, pain/pain-freeness) we think of as the basic, primitive norms guiding behaviour, but they are literally grounded in turn in the obtaining of autonomy, from which they derive their normative character.

*Wilfulness.* A will is the capacity to do work (that is, transform energy) in relation to the self whose will it is. The constitution of the autonomy constraint, which focuses directive organisation on generating behaviour to achieve self-regeneration, constitutes just such a distinctive capacity.

*Action.* The wilful performance of anticipative interactive activity against a normative evaluation criterion provides a root sense of action.

*Adaptedness, Adaptiveness.* An organism is adapted when it possesses an autonomy-satisfying set of traits in its life-environment. Conversely, an organism's ecological niche is comprised of the range of life-environments for which its traits provide satisfaction of autonomy. An organism's adaptiveness is its capacity to alter its specific traits in mutually coordinated ways so as to adapt to, that is, satisfy autonomy in, a wider range of life-environments than its current one.

The major challenge facing this approach to individuality is to link it to a detailed account of the globally coherent, spatio-temporally organised realising mechanisms, e.g. neural organisation, in an account of the evolution of organisms from elementary proto-cells to contemporary forms of life (cf. [Gánti, 2003; Bechtel, 2007; Bechtel and Abrahamsen, this volume]). This non-trivial task now constitutes a large research focus. Part of it is to re-think the nature of intentionality and intelligence on the basis of the evolution of neural tissue in both the visceral and central nervous systems (see [Moreno, this volume] and references). Here again the functional organisation of autonomy provides a scaffold for developing more detailed theories [Christensen and Hooker, 2002].

A *fourth* significance of autonomy is that its conception of agency just delineated fruitfully frames the evolution of intelligence and intentionality, thus also providing a framework for (organically) intelligent robotics. The underlying theme of the expansion of multi-cellular life forms is the massive expansion of interactive potential and competencies that will support more complex regulatory capacities and vice versa.<sup>68</sup> The increasing self-regulation of interactive capacity grounds their

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<sup>68</sup>Multicellular organisms differ in at least three important respects from single cells: they have (i) increased substitution of environmental construction for internal construction (e.g. carnivores intake complex molecules, humans rely on environmental production of many essential amino acids), (ii) increased self-regulation of their food acquisition and damage avoidance (e.g. rapid or prolonged migration to track food resources, hiding or hole construction to escape predators) and (iii) increased capacity to self-regulate the modification of metabolism to suit both tempo-

rich adaptabilities that make them so successful, and so intentional and intelligent in the way they are successful.<sup>69</sup> Becoming more specific, there are three major aspects determining a system's anticipative capacities: the width of its interactive time window, the degree of articulation of the autonomy-related norms which it can use, and the high-order interactive relationships that it can effectively regulate. Between them, these features characterise the dimensions of intelligent/intentional capacity [Christensen and Hooker, 2002; 2000b], and their roughly joint evolution traces the emergence of mind.

In this development two key thresholds are marked by the emergence of (i) self-directedness — the capacity to evaluate and modify interaction with the environment so as to improve basic autonomy-referenced evaluation — and subsequently by (ii) self-directed anticipative learning — the capacity to extend and modify anticipation, evaluation and modification strategy in the light of past interaction so as to better satisfy autonomy-referenced evaluation.<sup>70</sup> Moreover, autonomous systems can also be provided with action-centred informational and semantic characterisations, to complete the sense of agency. Organism information is modelled as reduction in downstream process regulation uncertainty. ('Shall I do A or B? Given the result of my last interaction, B is the thing to do.') Organism semantics is that of the anticipated norm-referenced, autonomy-satisfaction provided by an action. Intentionality is then conceived as a high-order regulatory capacity for

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rary activity (e.g. heart rate and blood re-direction for running) and permanent change (e.g. callousing, neuro-muscular compensation for injury). Underlying these is a fourth, more basic, way in which they differ, (iv) they have acquired the capacity to communally regulate the birth, specialisation and death of their members (cells). While in neurally more complex species they can show a myriad of forms, every viable community, including human communities, must acquire some form of these capacities. (Over the last century as human societies have become more developed, they seem to be experimenting with internal regulation of birth (aka the demographic transition), and specialisation (aka education) while decreasing regulation of death (no death penalty, euthanasia, + some regulation of war). Similarly, all the conceptions to follow grade back to the actions of single cells, though the stronger the self-directed, anticipative organisation involved the richer the semantic and informational structures sustained.

<sup>69</sup>The predominant effect of evolution is to expand the capacity for interaction with the environment, including both anticipating environmental courses of action and acting to modify the environment to shape its selection pressures. Here an issue arises concerning the nature and role of closures in biological organisation. The autonomy relation involves the closure of metabolic processes — since the outcome must be reproduction (notes 60, 61 references) — and the closure of the interaction process, since it requires feedback to have effect and to support learning. For Rosen [1985a] this last is the root of anticipation in interaction. There is widespread agreement about these closures, so long as they (the anticipatory loop especially) are construed to be compatible with the expansion of adaptive capacity. Beyond this, however, Pattee [1995; 1996] looks to specific self-referential closure within the cell as the basis of for-the-organism information and [Etxeberria and Moreno, 2001; Ruiz-Mirazo and Moreno, 2006] then extend closure further to that of neural function underlying intelligence, cf. [Pask, 1981]. Again, this might prove correct, but it is unclear that any defensible special notion of information is thus defined and it is noticeable for shifting the focus of attention to the obtaining of closure rather than to the expansion of interactive openness to the environment which is the functional focus of intelligence and intentionality (cf. [Hooker, 2009b]). Closure is for practical ends, not for its own sake. The issue needs further close consideration.

<sup>70</sup>For some more detail see section 4.1.3 below, where it is also applied to the scientific process.

fluid, meaningful goal-directed management of interaction and intelligence as goal-directed management of problem-solving capacity. Intelligence and intentionality co-evolve making use of a common self-regulatory apparatus. This avoids the common but implausible split between the two, respectively into problem solving and referential capacities. Agent actions are conceived as whole extended processes adaptively aimed at a goal (cf. [Juarrero, 2002; Van Orden *et al.*, this volume]), structured and regulated through anticipative potentiation [Hooker and Skewes, 2009].<sup>71</sup>

In sum, autonomy promises to provide the broad organisational framework from within which a fully naturalised conception of organisms can be developed in terms of the naturalistic inter-twined emergences and mechanistic reductions that reveal their biochemical organisational depth. Of course, from a scientific point of view, the devil lies in providing the details. And, as illustrated, the challenges in doing so run deeper than simply coping with complications.

#### 4.1.2 Cultural dynamics

The second of the ideas is that of cultural dynamics. Culture has largely been omitted from biological consideration, it essentially only appears as a source of specific ‘memes’ that impact genetic evolution, its only changes being in those memes.<sup>72</sup> Culture is a population-level phenomenon and a general memetic model of culture is popular because it appears to copy the established gene-centred biological theory of population dynamics, is relatively simple and marries simply to genetic dynamics when modelling evolution-culture interactions. But it is also a dynamically simplistic, partial conception of how culture is structured and works. The discussion of *super-system formation*, section 3 made clear that we are deeply embedded in culture, much more deeply embedded than memetic infection can express. The beauty of using complex dynamical models is that doing so opens up a wide variety of other interactive conceptions for consideration — e.g. rather than its being like catching a cold, perhaps our relation to culture is more like

<sup>71</sup>In this limited sense [Hooker and Skewes, 2009] can be understood as employing the notion of autonomy and the ensuing notions of intentionality and intelligence built on it in [Christensen and Hooker, 2002; 2004] to complement and complete the complex systems approach to action begun in [Juarrero, 2002] and extended in [Van Orden *et al.*, this volume]. In other respects there are many differences. Here the resulting interaction-centred semantics is very different from, and more powerful than, standard direct referential semantics, for it captures directly the unlimited implicit possibility content in our action-differentiated grasp on reality. Bickhard argues that in this way it resolves the frame problem, and is anyway ultimately the only coherent naturalist semantics, see e.g. [Bickhard and Terveen, 1995].

<sup>72</sup>For memetics, see e.g. [Aunger, 2000; Blackmore, 1999], cf. <http://en.wikipedia.org/wiki/Memetics>. Extant evolution-culture studies tend to emphasise one side of a dual-mode model (see e.g. [Lalande, *et al.*, 2000]), either focusing on genetic determination of culture — e.g. some sociobiology and evolutionary psychology — or conversely on the impact of cultural practices, e.g. mate selection and tool use, on gene frequencies through their modification of selection pressures. While understanding whatever constraints genetic inheritance places on accessible cultural expression, and conversely, are important, if difficult and controversial, studies, each provides only very partial insight into cultural dynamics itself.

being glued to a shared rubber sheet so that the movements of each refract to the whole and vice versa.<sup>73</sup>

Knowing that genes associated with flight capacity have increased (all that population genetics/memetics supplies) is not the same as providing an explanatory theory *of* flight, which in addition requires at least an aerodynamic account of what flight requires, a physiological account of how it is achieved and exploited, and an ecological account of when it is advantageous and why it can form stable niches. Without all these we cannot explain how and why flight developed (e.g. as opposed to gliding), what limitations it imposes (e.g. on energy budgets, hence food sources), what its range of expression is (cf. albatross versus humming birds), what are its characteristic failure modes (e.g. inappropriate pectoral blood supply for wind regime), etc. And without these understandings we cannot understand how its embodied expression might change. That is, we cannot formulate an adequate dynamics for it.

Further, explanation deeply involves integrated holistic processes that resist modelling as simple bundles of separate units, genetic or otherwise.<sup>74</sup> Like respiration (see section 3, *Multi-level* and *multi-order functional organisation*), culture is actually constituted by a widely diffused but socially integrative, multi-dimensional, multi-modal, multi-plexed, multi-produced, and multi-phasic complex of highly interactive and plastic, highly organised processes and concomitant states. Consider clothing as a typical human cultural feature: (i) Clothing serves many functions simultaneously (multi-plexed): body temperature control; injury protection; personal comfort; social role/status indication; aesthetic expression; individuality/deviance creation; ... In consequence it is also involved in modulating many different interactions simultaneously, e.g. interaction with the physical surroundings and in various aspects of social interaction. (ii) The realisation of

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<sup>73</sup>To illustrate the richness available, here are some simple proto-cultural dynamical distinctions. (SHMO = simple harmonic oscillator; DCC = dynamically collective constraint.) Model 1: a set of independent SHMOs. System state = aggregate of individual states. No DCCs. All collective phenomena are patterns determined only by initial and constraint conditions. Social example: the distribution of objects in refuse. Model 2: model 1 + small, local pair-wise interactions between SHMOs. System state = perturbation of model 1 state by addition of local pair-wise corrections. Weak local DCCs responsible for collective wave-like perturbation propagation. For increased interaction strength &/or less local interaction, stronger &/or more global DCCs emerge generating further collective phenomena, e.g. entrainment, chaotic behaviour. Social example: pair-wise reflex interaction behaviour. Model 3: model 2 + interactions modified by SHMO integrative memory. System state = joint product of SHMO states and interaction states. Memory is some function of past interactions and constrains current interaction form and strength. Emergence of global DCCs constraining SHMO behaviour in relation to collective properties. Social example: pre-recording socially referenced behaviours. Model 4: model 3 + integrative memory referenced to a shared global field. System state = joint product of SHMO states, interaction states, and field state. Field interacts locally with all SHMOs (realised, e.g., by a rubber sheet to which they are attached or an electromagnetic field which their movements collectively generate). Emergence of strong global DCCs constraining SHMO behaviour in relation to collective properties based on inherent field dynamics. Social example: socially recorded referenced behaviours.

<sup>74</sup>See e.g. [Ahouse, 1998; Ahouse and Berwick, 1998; Christensen and Hooker, 1998; 1999; Depew and Weber, 1999; Griffiths, 1992; Jablonka and Lamb, 2005; Miklos, 1993; Raff, 1996].



clothing functionality is multi-order and multi-level, requiring people with appropriate internal attitudes, preferences and behaviours; influencing performative aspects of every social activity (e.g. performing authoritatively in a business suit); and involving all of the processes that make up the fabrication, fashion, fabric materials production (including primary production) and recycling, industries. Many different interactive processes thus combine in complex ways to constitute an act or tradition of clothing (multi-dimensional), from production, to performing with and evaluating, to recycling. (iii) There is a large variety of clothing products and product attributes (multi-produced), from swimsuits to business suits to space suits. (iv) Clothing is involved in many different biological and social modes (multi-modal): differentiating work and leisure, dangerous work from safe work (and many forms of work, e.g. priest from pilot), and so on. It is also involved in many industrial production and manufacturing modes, from agriculture to petrochemicals, many different distributional modes, from commercial catwalk fashion to charity, etc. (v) This complex of interactive processes persists on many different timescales (asynchronous), from multi-generations for the overall structure of production + wearing/ performing/ evaluating + recycling, to the sub-generational ephemera of fashion attitudes and products. As technology, work role and lifestyle requirements have changed various aspects of this complex have radically changed organisation (non-stationary).

And of course we are not simply absorbers of culture but equally act to change it, and on many different scales from home behaviours to the conduct of global institutions. A cultural feature is the joint complex product of many groups acting for many different reasons, while also partially shaping them all. Thus we enjoy a delicate shaped/shaping dynamical relationship to culture, re-making it while it remakes us. Social constructability is necessary for possessing a culturally suitable plasticity, else the global constraining character of culture would lock its members out of shaping it and lock it in, emasculating genuine cultural participation. Constructability of itself does not however ensure suitably shapable plasticity; termite society is constructed by termites but is not culturally plastic. Culture requires a particular relationship between the responsive, constructive capacities of individuals and the globally binding capacity of the emergent society; too little binding and the society falls apart into a mere aggregate, too much binding and culture is squeezed out by merely rigid habits. But our shaping by culture is significantly plastic still; e.g. 'stone age' people can be taught to fly jet planes and even to adopt the jet-set social world. And our cultures are equally plastic and locally responsive to us and our environment (cf. clothing above). In such cultures powerful adaptive individual-group dynamics characterise all orders of organisation.

Culture plays an intimate role in our lives, not simply as mental contents but as embedded in our personality structure, general assumptions and orientations, and our methods and supporting skills and throughout our economy. Understanding cultural change involves characterising such features as clothing dynamically, placing the interactive complex of these cultural features in their organismic, communal and ecological settings, and capturing the delicate shaped/ shaping interaction dy-

namics that makes human cultures so powerfully creative and adaptive. That parts of clothing, such as hats, can be artificially extracted and their changes recorded no more shows the legitimacy of disassembling cultural features into bundles of objects and ideas than the study of hearts does in the case of the evolution/development of respiration or flight. We should not, e.g., rush to evolutionary heritability conclusions about culture just from patterns of sequential repetition with modification; ripples on a shelving beach show these, as will all similar spatially constrained succession, like urban expansion, plus all processes of self-organisational re-assembly, such as rush-hour queues, all processes of path-dependent biased copying, such as housing design, etc.<sup>75</sup> Instead of the relatively external relationship of infection between cultural memes and persons we may contemplate culture as shaping constraints, mutual entrainment couplings, self-organising path-dependent features, and the like. The bad news arising from this is that our modelling of cultural dynamics is as embryonic as is our biological modelling generally in these respects. The good news is that culture reveals a fascinatingly complex dynamical reality for study.

Though capturing cultural dynamics is thus daunting, its biological roots provide clues for at least beginning. The shaped/shaping dynamics underlying culture is as old as life itself. Every living entity is internally organised so as to match boundary behaviour to those interaction modes with its environment that will deliver needed resources while avoiding injury. Boundary-mediated, inside is functionally shaped to outside — but in order to preserve inside autonomy invariant, that is, independent of outside. Conversely, outside is altered by, and often shaped by, inside-directed actions, creatures internally regulating this inside/outside tuning in ways their inanimate environment cannot. Beyond any general naturalist leanings, the deep-seatedness of this complex dynamic suggests that we start there when trying to understand cultural change. In this setting culture is modelled as one class of complex shared integrative features of biological communities and it is the dynamics of these that must be captured.<sup>76</sup> But human agents are cognitively and strategically powerful enough to possess self-directed anticipative learning (see below). Beyond the basic task of differentiating and capturing the relevant biological dynamics lies the challenge of understanding the implications of such capacities

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<sup>75</sup>Beach slope and water viscosity are factors in the explanation of ripple succession, but very different factors from those generating genuine lineages, let alone from those reproducing generations as combinatorial assemblies. Whence genuine lineage heritability requires Wimsatt's generative entrenchment conditions [Wimsatt, 1999] to *at least* be embedded in his assumed condition of an ongoing reproductive process, and arguably also requires generated autonomy so as to provide a principled sense of within-lineage individuality and of regulatory entrenchment which is genuinely (re)generative. And this is just the beginning to exploring biologically relevant constraints. How much constraint, e.g., can other self-organisation processes apply and a selection process still be claimed operating? Some theorists (the range extends from Wimsatt to Pattee) may still hope to show that there are informational units playing gene-like roles inside every social process, but this remains open and ambitious.

<sup>76</sup>Hooker [2002], on which this discussion is based, offers 5 basic relationships among autonomous systems (creatures) whose dynamics, once captured, might form the basis for a first agent based modelling of cultural interaction.

for human cultural dynamics. Those dynamics are at work everywhere, but they are pre-eminently displayed in science, that supreme cognitive cultural creation.

#### 4.1.3 *Science dynamics*

The third of the ideas is that of the dynamics of science. Science is part of human culture and you would therefore expect to model its dynamics in similar ways. It is clear, even to casual inspection, that science is thoroughly dynamic, transforming itself from bottom (data) to top (meta-method, metaphysics), moving through major upheavals — some called revolutions, like the classical to relativistic and quantum shifts — and speeding up the process from centuries initially (e.g. the classical to relativistic shift) to decades now (e.g. the genetics to systems/ synthetic biology shift). Moreover, this is not just a matter of grand theory change, there are other, equally or more important changes also involved. Consider, for instance, the evolving role of the senses in science. On the one side there has been an increasingly refined critique of natural sensory perception for its limitations (e.g. limited discriminations), biases (e.g. tracking delays) and imperfections (e.g. illusions). Technology and theory were essential here, e.g. the camera and optics for detecting perspectival bias, infra-red and x-ray technologies and backing theory for the use of the non-visible electromagnetic spectrum. On the other side there is the development of extensions to, and substitutions for, the senses, e.g. telescopes, microscopes, micrometers, x-ray photography. These allow us to confine use of our senses to those narrow circumstances where they work best (e.g. identifying and counting appropriately shaped and coloured human-sized objects). This dynamic has been going on for centuries, interacting with theoretical developments, but as often initiating them and overall uninterrupted by theoretical and other upheavals. Another similar dynamic has been the elaboration of method.<sup>77</sup> The impact of change of method is nicely illustrated by the impact of complex systems models on archaeology [Hooker-b, this volume, section 5.1.3]. These two processes bid fair to be the great ‘bedrock’ drivers of scientific change, with data and theoretical shifts playing higher order steering, and less frequently fundamental, roles.

Here a biological orientation provides a larger setting. Cognition evolved because adaptive control of behaviour was reinforced. Central to that control is anticipative intervention to alter the body-environmental relationship, not only by moving the body about but also, from early on, to disturb the environment in order to profit by its response and, then, to learn from its response and, subsequently, to deliberately modify the environment so as to reduce risk and enhance

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<sup>77</sup>For review and references see e.g. [http://en.wikipedia.org/wiki/History\\_of\\_scientific\\_method](http://en.wikipedia.org/wiki/History_of_scientific_method), [Blake, *et al.*, 1960; Oldroyd, 1989]. Many contemporary Companions, Encyclopaedias, etc. of philosophy of science do not consider the topic. In these references method is primarily considered to be concerned with theory-experiment relations, but it ought to be expanded to include experimental design and theory of errors, all critical factors in the conduct of science and hence of scientific learning about learning (e.g. [Mayo, 1996; Farrell and Hooker, 2009] and references). These latter two, plus instrumentation (theory and practice), form the ‘engine room’ of science.

reward (e.g. nests and burrows, food caches and mating bowers). From this flows the central role of technology in the scientific process. Our earliest technologies were provided by our bodies. Subsequently they evolved as exo-prostheses. Technologies are essentially amplifiers. With respect to science they (i) extend its information base through instrumentation, e.g. electron microscopes, (ii) extend accessible methodologies, e.g. through numerical approximation techniques and automated data processing, (iii) generate new concepts, e.g. computer models of cognition, (iv) extend epistemic processes, e.g. through supporting global communications and (v) provide the resource base for scientific activity, from economic surplus generally to rare earth metals and other specific resources. Conversely, the development of technology is directly impacted by science through (i) new theoretical conceptions, (ii) new theory-driven designs and (iii) performance evaluation and re-design learning (fluid mechanics gained more from the development of reliable aeroplanes than vice versa). This co-evolution of method, theory and technology is of the essence of science and a vivid demonstration of its open-ended dynamicism.

So we need to think of science in these respects as a dynamic system, transforming its own instrumental ‘body’ as it evolves/develops, in delicate and increasingly intimate interactions with its transformation of its experimental and theoretical practices and its epistemological evaluative processes. And of course in strong positive feedback interaction with its economic and social environment through the supply of applied science and the feedback of funding and supporting institutions. Through technology science transforms its social and natural environment (e.g. respectively motor vehicles, world agricultural gene trade). This is the great Change Engine that is science-technology-economy. Not to take a dynamic process view of science will be to miss all this. And more. Science also transforms the policy processes that contribute to the dynamics of its environment (e.g. development of economic modelling for policy determination). And through the development of various science studies and science policy studies, which together form the so-called science of science, it is also transforming its own institutional design and social relations (e.g. respectively, the trend to larger specialised research groups, governmental science advice processes) including its own social evaluation. This sophisticated and thorough transformative capacity is a crucial part of understanding science as an increasingly autonomous, dynamic cognitive system.

But this perspective is wholly foreign to the traditional epistemological conception, the logic-centred conception, of science. The traditional models of science that consolidated and dominated in the period 1920-70 were all versions of an abstract, formally (logically) structured, a-temporal machine. In its empiricist version it takes empirical data and mathematical truths as input and, using formal inductive logic, outputs a best theory plus a specification of the best next experiment on that theory (or, where appropriate, a set of equal best theories and next experiments). In its falsification (Popperian) version it takes hypotheses, empirical data and mathematical truths as input and, using deductive logic, outputs a pass/fail verdict together with a next severest test for a passing hypothesis and

a next hypothesis re-setting for a fail. (But not the next hypothesis to test, being beyond deductive logic it is generated randomly with respect to the preceding.) In each case the rational decision making of individual scientists is modelled by a universal abstract rational agent following its formal procedure [Forster, this volume]. While this ‘method machine’ is assumed to be a computational process, this is in the timeless sense of logical sequence, not in the dynamical sense. Thus this dominant tradition was inimical to taking a dynamical approach to understanding science.

True, a very weak sense of timing could be had by tagging the sequence of theories generated with successive times, but this was always an abstract normative sequence, never a real historical one and was soon shown inadequate to the richness and messiness of actual history. The epistemic power of science lies in the way it builds, not just new descriptive theories, but new concepts and new methods, including new inference patterns, to suit what it discovers, *and* becomes better at doing all this as it goes along — no eternal formal inference machine can ever truly illuminate that. But the point here is that its formality prevents even recognising such transformative dynamics, which ultimately have to be carried by human creativity. It is diagnostic that any attempt to introduce psycho-social processes to the method machine was dismissed as confusing the merely empirical detail of implementation with the overriding normative task of determining epistemic warrant (or worse, claiming it relevant only when it represented interference with normative process). When Kuhn famously concluded that a scientific revolution could not be understood as such a formal machine process, it was not instead proposed to be some other kind of social learning process, but was instead demoted or dismissed as ‘irrational’, outside the study of scientific epistemology.<sup>78</sup>

The first important move away from this conception from the process point of view was the growing insistence by historians and some philosophers of science that they deal with individual scientists and laboratories in their social milieu, understanding their arguments and decision making as responses to their respective situations, e.g. [Galison, 1987; Shapin and Schaffer, 1985] However, these changes were conducted during the time in which the traditional model was under attack from all sides, various anthropological, historical, social, cultural, feminist and post-modern approaches jostling for attention. All of these derived from humanist sources, innocent of any dynamical sense even when using vaguely systems terms, and were predominantly understood in the humanist context. Thus the focus of discussion was on the social and symbolic nature and role of cognition, not on the implied dynamical nature of the processes involved.<sup>79</sup>

<sup>78</sup>See [Heunighan-Heune, 1993; Kuhn, 1962; Lakatos and Musgrave, 1970] and e.g. the Stanford Encyclopedia of Philosophy at <http://plato.stanford.edu/entries/thomas-kuhn/>.

<sup>79</sup>Latour, for instance, introduces laboratory studies conceived as anthropological field work, considers each individual decision maker present, even including investigated bacteria. See [Latour, 1987; Latour and Woolgar, 1979]. But these are treated as social agents and modelled as making decisions in the light of information available, their understanding of the situation and their interests (aka utilities, values). This isn’t yet dynamical, because social ‘games’ were thought of at the time as intentional and strategic, capacities that were tied to the non-dynamical

But from the later, larger perspective of the dynamical modelling of processes throughout the sciences, these moves can be seen as the first important moves toward a more dynamical modelling of scientific process itself. For if one wants to model science as some kind of interactive process, then the first step is to focus on the interactors, the active components of the system. Rather than simply accepting the stable collective features of the whole system (when it is ‘running smoothly’) as the basic structure for epistemology, as the traditional approach does, it would instead be viewed as an emergent macroscopic feature generated by actor interactions. Epistemological understanding, if any is to be had, needs to be re-grounded in the underlying actors and to characterise the collective level as emerging from their activities. But this radically reverses the natural position of the traditional approach since normative epistemology, being transcendent, holds ‘above’ even science as a whole and has a one-way relation of obligation on, and thus critical evaluator of, individual efforts. Unhappily, instead of siezing this reversal to open up dynamical process modelling of scientific process, the actors in this meta-science process drove it toward portraying science as simply one social ‘game’ among many others (the ‘strong programme’ in sociology of knowledge). Here there is no interest in game dynamics (cf. [Harms, this volume]), only in assessing the games’ status. Old-style formal normative epistemology was to be abandoned, or at least suspended.

Set aside that historians and anthropologists are not equipped, or inherently concerned, to treat epistemology. That they could not find the macro epistemology of the traditional model among their agent micro constituents is in retrospect to be expected. It is expected because re-understanding the macro phenomena is a characteristic issue for any dynamical micro account of a stable macro feature, typically involving emergence and functional reduction. That it should engender talk of abandoning epistemology is diagnostic, not only of professional disinterest, but of the lack of this modelling perspective. Nonetheless, the response was understandable in context. Not only was attention distracted from dynamical modelling by a myriad contentious meta-perspectives, there were few models to follow. Even today, after multi-agent modelling is well established in social science, the vastly intricate organisation of science places it as yet well beyond any detailed modelling capacity that might illuminate its distinctive cognitive and epistemic capacities. Compared to other domains, there are only simple, crude models to expose that cannot do justice to the complexities and nuances of real historical and laboratory situations, or even of the abstract network structure of science. Nonetheless, a range of simplified intermediate models have been proposed pro tem for approaching the modelling of scientific activity in complex dynamical terms. These draw their inspiration from complex systems models in related domains and include cybernetic, matter-energy web, evolutionary and emergent multi-agent models.

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world of thought and social norms. Yet it nonetheless represented a radical shift away from the traditional approach — so much so that Latour called for a moratorium on further traditional epistemological study of science. Today we might instead read much of Latour as incipient multi-agent dynamical network modelling.

These will be briefly reviewed in that order.

*Cybernetic modelling.* Beer was a prominent exponent who modelled an organisation as a collection of necessary functional modules that must all specifically dynamically interrelate so as to collectively constitute a viable system.<sup>80</sup> Largely focussed on business organisation, this model was nonetheless intended to be universally applicable and so applies to science as a viable organisation (cf. [Leonard, 1999]). Its functional categories are too general and its modularity too divisive to realistically model real scientific institutions, where functional multi-tasking and multi-plexing is too widespread and interrelationships are idiosyncratically both local and international. Nonetheless, it gives the sense of a dynamic regulatory system and validates the search for dynamical features like modularity and networks, communication, feedback and regulation.

Hooker [1995] represents a sustained attempt to provide a biologically grounded dynamical regulatory model of science inspired by the earlier cybernetic work. The fixed macro architectures of Beer's approach are eschewed in favour of more fluid biologically oriented process architectures, but regulatory functioning remains at the centre. Hooker shows how Rescher [1977], who shifted the focus of change from theory to method (in partial defiance of the eternal logic model), provides a valuable key to a still more thoroughly regulatory conception of science. Here scientific development is modelled as a multi-layered regulatory process spanning meta-method (including mathematics), meta/proto-physics, method, theory, experiment and data layers, all mutually interactive, each storing sophisticated regulatory information within and between them. Piaget is revealed as a pioneering interactive, regulatory biological theorist (see also [Hooker, 1992]). (His later 'stages' model of development is then viewed as a partial, crude aberrant return to a non-dynamical, logic-based framework.) From this perspective Piaget can then be understood as developing a conception of reason as a regulatory process that generalises well to a dynamical regulatory setting. And Hodges and Hooker show how even Popper had begun construction of a conception of social 'soft' regulation that provides a natural generalisation of engineering regulation suited to science as a social process (and quite at odds with his better known evolutionary views — see below).<sup>81</sup>

*Matter-energy web modelling.* Subsequently ecology developed a related interest in matter-energy flow food-web models (e.g. [Odum, 1971]). [Gao, 2005; Gao and Herfel, this volume]), for example, describe later work by Pahl-Wostl that constructs dynamical energy-material-information flow models forming spatio-temporally organised trophic dynamic modules in ecological networks. Pahl-Wostl argues that individual organisms' activities are the driving forces responsible for the emergence of this ecological organisation. Gao shows how this applies to science as an analo-

<sup>80</sup>See e.g. [Beer, 1972; 1979; Espejo and Harndon, 1989] and [http://en.wikipedia.org/wiki/Viable\\_System\\_Model](http://en.wikipedia.org/wiki/Viable_System_Model).

<sup>81</sup>Hodges [1997] develops in part an analysis of philosophies of science across the late twentieth century as essentially providing increasingly elaborated feedback quality controls on scientific development. For the discussions of Rescher's method dynamics, Piaget's regulatory rationality and Popper on soft control see chapters 4, 5 and 3 respectively of [Hooker, 1995].

gous networked system and provides insight into the laboratory, disciplinary and communicational organisation of science.

*Evolutionary modelling.* A rather different approach is represented by evolutionary models of scientific knowledge, known as evolutionary epistemologies. These are explicitly focused on the cognitive/epistemic content of science, unlike the preceding models, but share with the preceding models a first, rudimentary sense of a dynamics of science.<sup>82</sup> The simplest and most common of these models postulates a minimal, selective or partial analogy between genetic and knowledge processes, namely a common process of variation, selection and retention [VSR]. The idea is essentially that of the memetics model discussed under 4.1.2 above: cognitive memes evolve in direct analogy to the process for genes, with V = proposed ideas (hypotheses, etc.), S = experiment, R = accepted knowledge, so that VSR is the basic process of trial-and-error learning. The point of employing only a selective analogy is to avoid, e.g., having to find cognitive analogs for either the genotype/phenotype distinction or for the failure of transmission of information from cognitive phenotype to genotype. Many prominent evolutionary epistemologists occupy this cautious position<sup>83</sup> and it has interesting applications, e.g. to steam locomotion [Cragg, 1989]. Nonetheless, it is dynamically the crudest model kind with all of the defects noted under the discussion of culture above. In particular, these are disembodied genes/memes without embedding phenotypes, communities and ecologies to shape their dynamics. But, as just noted above, we must expect the embodied capacities of scientists and their communal institutional organisation to play important roles in science dynamics. In fact, expanding phenotypic capacities results in increasing internal regulation of VSR processes,<sup>84</sup> a crucial development unavailable to these models.

An obvious augmentation of the basic model is to introduce a genotype/phenotype structure to cognitive processes so as to extend the analogy. Toulmin [1972], e.g. takes the units of variation to be individual concepts, the genotype a relevant constellation of ideas and the phenotype roughly a particular theory and perhaps its applications. For Hahlweg [1983] the genotype corresponds to the entire realm of language and the phenotypes are actual scientists with their epistemic commitments and practices. There are many other versions, including from evolutionary economics (e.g. [Nelson and Winter, 1982]), adding to the foregoing array such analogical genotypes as mnemotypes, rules and routines, and such analogical phenotypes as artifacts and institutional actions. Since we now have parallel, but apparently unconnected, processes running on very different biological and cogni-

<sup>82</sup>For overview and analysis see [Hahlweg and Hooker, 1989a; cf. Hooker, 1995, 1.2].

<sup>83</sup>See e.g. [Campbell, 1974; 1977; 1986; 1997; Campbell and Paller, 1989; Rescher, 1977; Popper 1979; 1984; 1987]. The crude VSR process model suits Popper because he regards hypothesis creation as effectively random. Campbell has the merit of recognising multi-layered organisation in both processes and that these are efficient ways to store sophisticated regulatory information (cf. [Harms, this volume; Hogeweg, 2002b; Hogeweg and Takeuchi, 2003]). However the basic crudities still overwhelm the position [Christensen and Hooker, 1999].

<sup>84</sup>Cf. [Harms, this volume] on phenotypic capacities and on this internalisation of VSR process see [Christensen and Hooker, 1998; Bickhard, 2001; 2002; Hooker, 2009b].



tive substrates<sup>85</sup>, and with none of the predecessor defects addressed, these models need specific evidential justification if they are to be adopted.

An importantly different extension of the basic analogy adds phenotype capacities to both biological and cognitive evolutionary processes. This recognises that selection acts on the phenotype, not on the genotype directly. Conversely, variations cannot become eligible for environmental selection unless they have first led to a viable embryogenesis producing a viable phenotype. Hahlweg later developed a theory of this kind (see [Hahlweg and Hooker, 1989a, part II; Hahlweg, 1991]). Notable about this conception is the distinction between adaptation and adaptability (adaptive capacity), together with the thesis that in certain circumstances adaptive capacity can accumulate under VSR while adapted capacities remain non-accumulative. In itself these are welcome sophistications of each process that begin to relieve the charge of dynamical crudity, as well as speak to the huge accumulation of adaptive capacity represented by the history of science. However, it also draws attention to the concomitant necessity of introducing the material communities and ecologies that phenotypes use and reconstruct to modify selection pressures, the one concrete the other abstract, and in doing so re-emphasises the original awkward dual substrates parallelism left untouched.

It makes sense to solve the parallelism problem by doing away with two processes in favour of one. That is to view knowledge as simply one aspect of biological life that emerges as phenotypic cognitively-based capacities increase, and view science as its concrete institutional communal/species form. Evolution is also taken to be a multi-layered development of regulatory systems, from intra-cellular to ecological (local, regional and planetary). From this point of view science represents an extension of regulatory complexity driven by information expansion, intensification and compression (into laws). Mathematics vastly extends our theoretical regulatory capacity while technology vastly extends its material reach, together enlarging our possibilities for further regulatory expansion. This unified evolutionary orientation is essentially that used in Hooker [1995], reviewed above, so long as it be remembered that expanding phenotypic capacities results in increasing internal regulation of VSR processes, so it is that regulation that takes centre stage.

*Emergent multi-agent modelling.* One way to develop the general regulatory-evolutionary approach above further is to exploit the idea that the epistemic process of science emerges from the material process, analogously to the emergence of multi-agent dynamics or market pricing. An embryonic version of the former alternative is offered by Herfel and Hooker [1996; 1999]. They explore the general (abstract) productive dynamics of consensus and dissensus in a multi-layered regulatory system (each of meta-method, method, theory, data used to generate and

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<sup>85</sup>Popper [1979], e.g., makes the gulf literal, placing the biological entities in his worlds 1 and 2 (respectively, material and psychological) and the intellectual entities in his world 3 (abstract). He connects world 3 to worlds 1 and 2 by a 'Principle of Transference' which simply baldly asserts that what is true logically in world 3 is true causally in worlds 1 and 2. But this *labels* the problem rather than solves it (cf. [Hooker, 1981a; 1995, chapter 3]).

critique adjacent layers), and the prospect of modelling scientific revolutions as analogous to phase transitions within the system. Analogously to Hahlweg's accumulatory adaptiveness, but now concrete, what is progressive over the longer term is the superfoliation of the regulatory structure itself. Shi [2001] provides a more direct model of the self-organised emergence of institutional rules and cognitive regulation in science from a multiplicity of partially locally coordinated interactions among diverse strategic researching agents. This is done within a broadly economic approach to interaction. The emergence of price in the market is the model for self-organised emergence of social regulation. Here individual scientists are seen to play several entrepreneurial and consumer roles (e.g. investing in experiments, consuming each other's information). Between them these agents generate and stabilise institutional functioning. This functioning is summed up in its three kinds of rules: resource distributive (e.g. dollars and devices), cognitive constitutional (e.g. reliability and reproducibility) and evaluative aggregative (e.g. propriety and prestige). This lays the foundations for more detailed multi-agent modelling in future. As these rapidly developing modelling techniques mature (themselves the product of science), a key issue will be whether earlier features are also to be understood as emergent within a Shi-style approach, e.g., that revolutions will be incorporated as self-organised constitutional change and the earlier energy-materials-information flow work will be understood as a product of resource distribution.

Another, complementary, way to develop the position is to consider the methodological organisation of research activity, as founded in individual capacities. Recall that autonomy (see section 4.1.1 above) is a global organisation of sensory and motor capacities linked to satisfying metabolic requirements, and that these capacities have become more sophisticated over time, especially in the mammalian evolutionary lineage, currently culminating with humans. Two key organisational steps toward human cognition are the functional capacities of self-directedness and self-directed anticipative learning [SDAL]. These capacities are characterised by an increasingly sophisticated regulation of success and error feedback that effectively constitutes an internally regulated VSR process.<sup>86</sup> In particular, SDAL gives rise naturally to a methodology for solving open problems, the basic kind of relatively ill-defined problem faced in research, and in fact throughout life. (However such problems are notoriously inaccessible to logical method and to formal cognitive science more generally.) SDAL provides the basic model for the organisation of research activity. Science can then be understood as a complex of partially and multiply interrelated SDAL cyclings, driven by individuals operating in the institutional settings of laboratories, universities, societies, etc. This recent view has already garnered some instructive empirical support, but also poses special challenges to dynamical modelling (see below). It is now briefly presented.

Primitive creatures have stereotypical responses but more sophisticated creatures can shape their behaviour to suit their circumstances. The basic dimensions

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<sup>86</sup>On SDAL see note 51, on internal VSR regulation see [Hooker, 2009b], cf. Bickhard's alternative conception of error feedback at note 84.

to this shaping capacity are the capacities to (i) dynamically anticipate the interaction process, (ii) evaluate interaction using normative signals and (iii) modify interaction in the light of (i) and (ii) to satisfy metabolic requirements. Organisms with this three-factor shaping capacity are *self-directed*.<sup>87</sup> Mosquitos hunting blood hosts are not self-directed, their behaviour is stereotypical. By contrast in cheetahs hunting prey we see the integration of evaluative and situational information with powerful anticipation to produce fluid goal-directed hunting interaction. Because cheetahs differentiate many kinds of variables (e.g. concealment, terrain, prey alertness, speed, agility, and aggressiveness) and anticipate their influence on hunting (e.g. on isolating a prey from its herd) they are able to act fluidly and appropriately in a complex and changing hunt. Cheetahs are powerfully self-directed hunters. Successful adaptive shaping is problem solving and these are the ingredients from which cognition is formed.<sup>88</sup>

Cheetahs are also powerful learners; a cheetah cub lacks most of the skills required for hunting and must acquire them through learning in practice. But powerful learning is only possible because the cheetah has the capacity to use evaluation of feedback to modify its own self-directedness, that is, modify its own anticipations, its evaluative signals and its existing behaviour modification procedures. Bumble bees are simple self-directed agents, since they can learn which flowers currently offer the best nectar rewards by evaluating the results of their flower searches, but they cannot learn to anticipate flowering patterns (e.g. by species, season and location), or modify or extend their operative norms, or modify their learning strategy. Cheetah cubs can do all of these things. They are *self-directed anticipative learners* [SDAL].<sup>89</sup> There is a virtuous feedback circle here, for as the cheetah gets better at differentiating the relevant factors in effective hunting it not only becomes better at hunting, it also becomes better able to recognise sources of error in its hunting technique and hence improve it. Cheetahs

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<sup>87</sup>They are directed because they are thereby powerfully organised to direct interaction into autonomy satisfaction, and self-directed because these are internal processes and their locus of regulation lies primarily within the organism itself.

<sup>88</sup>There is thus no single 'mark of the mental', instead there is a group of capacities that become specialised in various ways through evolution over the long run and, as regulatory sophistication increases, also increasingly during individual development (using individually and communally regulated VSR processes). See [Christensen and Hooker, 2002].

<sup>89</sup>See [Christensen and Hooker, 2000b; 2002]. Introduced by Christensen [1999], the particular synergism of this converging cycle of improvement was a refinement of its preceding convergence models, see [Hooker, 1988; 1995, chapter 4]. Another more sophisticated example is that of a detective conducting a murder investigation. The detective uses clues from the murder scene to build a profile of the suspect and then uses this profile to further refine the direction and methods of the investigation. (A receipt may be enough to re-direct the search from lovers, using personal network construction methods, to business creditors, using financial analysis.) The profile tells the detective what the murderer is like and what types of clues to look for. This in turn sets new intermediate goals that focus the investigation. If the profile is at least partially accurate the modified investigation should uncover further evidence that in turn further refines the search process, ultimately (hopefully) culminating in capture of the murderer, and revealing how and why the crime happened. It is the interplay between the discovery of clues, the construction of a suspect profile and subsequent modification of the anticipative investigation strategy that provides the process its self-directing power.

learn how to learn better in the process of learning how to do better. SDAL uses interaction to acquire information about the nature of the task as well as of the specific performance to hand, and thereby improves performance.

Just this is the virtuous bootstrap that must be behind every capacity to solve open problems. When successful, SDAL results in a pushme-pullyou effect as learning is pushed forward by the construction of new anticipations and pulled forward by the environmental feedback generated, creating an unfolding self-directing learning sequence. Because of its characteristic self-improvement SDAL can begin with poor quality information, vague hypotheses, tentative methods and without specific success criteria, and conjointly refine these as the process proceeds. This makes SDAL powerful because it allows successful learning to arise in both rich and sparse cognitive conditions. These are the conditions met in scientific research. Uncertain about valid methods and relevant data, let alone true theories, researchers behave like cheetahs (and detectives — note 89). (I) They search for features that might provide useful clues and evaluate their significance against previously accepted criteria. (II) They then build a tentative theory-linked model of the situation based on the available evidence and accepted theoretical and practical options. (III) In that light they decide a tentative methodology for investigation. (V) They then rely on evaluating feedback from experiment to refine the model and investigative methods. If this continues successfully they will close in upon the real nature of the problem and its proper categories, theory and methods. If improvements stall, they return to (II), re-evaluate the now larger body of evidence, develop a new model and continue the cycle.

The SDAL model has been tested against a new analysis of the early history of ape language research and shown to provide deeper illumination of its processes than does conventional analysis, indeed to lead to an improved account of error management in science [Farrell and Hooker, 2007a; 2007b; 2009]. In this case the SDAL synergy between (i) learning improved interaction (experimentation) methods and (ii) learning how to learn about investigating intelligent, social animals, proved particularly powerful. It led to the transformation of the ‘profile’ of the nature and role of language in a social community in a way that opened up a radically new methodological space. This is the essence of SDAL learning.<sup>90</sup> Moreover, SDAL cycles can for this reason operate across so-called revolutionary periods of change as well as across the less transformative ‘puzzle-solving’ changes. This demonstrates a deeper SDAL-cycling organisation to science, reveals a rational sub-structure to scientific revolutions, and explains the way in which the learning capacity of science improves over time in tandem with the adequacy of its content.

These are early stages in developing an adequate dynamical model for science. An obvious next step is to attempt to combine the emergence model of dynamically stabilised macro organisation with the SDAL model of research process organisation and dynamics. Although dynamical in spirit, the realisation of any more

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<sup>90</sup>It also focuses attention on methodological change as a, often the, principal driver of scientific change (as opposed to the primary emphasis on theory change in the standard approach). And the result is again a thorough individually and communally regulated scientific VSR process.

quantitative dynamics must likely await the development of multi-agent network models for these features. This will be no simple task. First, constructing a network dynamics will be challenging since these networks are ephemeral and highly idiosyncratic to content. For instance, at one point as research on ape language developed it became relevant to pay attention to the distinction between receptive and expressive competencies in the context of developmental linguistics and at another to expertise in non-linguistic behavioural signalling [Farrell and Hooker, 2007a; 2007b], extending the research network in these highly content-specialised ways for that time. In sum, scientists form relationships based on any and all of the specific methods they use, theoretical models they employ, problems they have, accessible useful data bases, and so on. Some of these will be long-term, but many will be ephemeral and opportunistic. They may involve specialists in other areas of their own discipline or domain or in ‘distant’ disciplines and domains (because, e.g., they share the same tools or related problems). And they can change in the same highly idiosyncratic ways. A single visit to another laboratory to learn a new technique can transform an entire research programme and its network. These networks will form no simple patterns, and if e.g. ‘small world’ phenomena indicate that a scientist talks a lot to just a few others, this will in itself be almost wholly uninformative about the importance and dynamics of the resulting science.

There is also the issue of representing the process of creativity within SDAL cycling. Any attempt to model it potentially reduces it to a mechanical process, something that has proven thoroughly elusive to date. It seems that it would do no better justice to it if it were confined to self-organisational processes. Finally, in the eternal formal method/AI machine conception, normativity derives from some realm radically disjoint from (and transcending) factual considerations. With that approach rejected, there arises the inherited issue of how to extract epistemic normativity from *prima facie* non-normative, because dynamical, processes. But meeting or failing autonomy requirements provides an inherent biological source of normativity, since this condition is a *sine qua non* for all else. This, elaborated through Piagetian developmental process and communal self-organisation of rules, can eventually support the elaboration of ideals like knowledge and truth and their operational surrogates like testability and confirmation that we in fact see in the historical record. Moreover, it renders them fallibly learnable and improvable, to allow modelling, and ultimately explanation, of that history. All together, this approach develops an appreciation of the open-ended complex knowledge generating system that is, in all its messy but wonderfully complex reality, science.<sup>91</sup>

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<sup>91</sup>Bradbury says, science is itself a complex system because only a complex system can investigate a complex system [<http://www.tjurunga.com/biography/roger.html>]. This may well be so, but it is nontrivial to clearly show. It is tempting to appeal to some version of Ashby’s Law of Requisite Variety (see e.g. <http://pespmc1.vub.ac.be/REQVAR.HTML>), but this has to be done carefully. For instance, since it is possible to control very complex systems with very simple (but rapid) curve-tracing procedures requiring few distinctions to deploy, if the goal is simple enough the variety that is requisite can be small. The amoeba controls its behaviour on the basis of just one distinction: membrane irritation or not, and this suffices for survival in very complex envi-

## 4.2 *Six scientific domains where complex systems are challenging and enriching science*

This book would have been more complete if, among the large number of further essays that could legitimately have been added, six in particular had been included covering complex systems in the domains of physics, chemistry, geology, engineering, neurophysiology/neuro-psychology and social science. These essays were diligently pursued but nonetheless did not eventuate. In what follows I provide very brief notes on these domains indicating at least some reasons why they ought to be included. I do not pretend to offer an integrated or penetrating overview — that would be to presume to an expertise I don't have. And, given that some of the literatures are already vast and some hidden away in 'corners', it would also be to presume to exploration time I don't have. These notes are simply designed to set out some issues that are distinctive to the domain and otherwise allow an interested reader to start burrowing into the literature for themselves.

### 4.2.1 *Physics*

Manifestations of complexity are surprisingly rare in traditional physics. Typically, it is possible to study the whole of mechanics — classical, relativistic and quantal — without meeting a single complex system. The primary reason for this is surely the clash between the presuppositions of the analytic core dynamics these approaches all share and the conditions under which complexity phenomena typically occur (see *Constraints*, section 3 and [Hooker-c, this volume]). Whence the primary topic for complex systems is to understand this issue and what might be required to resolve it. This is an extremely difficult matter on which few are able to offer systematic insight, even among those with relevant mathematical expertise. In the classical domain Newton's equations apply to all systems, so we can easily define functional solutions for them: the functions for a system S, no matter how complex, are whatever solve the S equations of motion. The trouble is, for almost all systems S, no one knows how to extract much information about S from these 'easy functions', especially for complex S. In short, we have no general the-

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ronments. But if we take the goal of science to be maximal knowledge and maximal control, then we might appeal to an expanded form of the law along the lines: a scientific knower must have at least as much internal organisation as the system it wishes to know. Other applications include models whose behaviour can only be simulated not deduced, models so complex they can only be specified or constructed in the same time periods as they took to evolve, and models so complex they can only be investigated similarly to the investigation of reality. Under the rise of complex systems models, each of these cases is becoming increasingly frequent. Such phenomena are at least an antidote to the long diet of culturally inspired models of science. Jacob Broinowski, defending his approach to science, offers as a principle justification that "... language is a more telling, and a better model for science than is any mechanism." [Broinowski, 1965, p.176] With respect to the basis in language that Broinowski had in mind, it can now be understood how profoundly mistaken is this well intentioned pronouncement (though issues over mechanism persist). However, in keeping with the counter-intuitive character of the complex systems domain, note that in the light of [Lansing, this volume], should network dynamics develop into a mature pan-domain science including linguistics, it might yet still be true.

ory of classical non-linearity. The problem is only deepened when we contemplate the determined linearisation of the quantum operator dynamics confronting the equally determined non-linearisation of dynamical space-time in general relativity.

In practice, mathematical research is split among a number of disparate areas, including non-holonomic Lagrangian theory, effective Hamiltonians, non-linear and irreversible semi-groups, irreversible dissipative systems (initiated by Prigogine's group), irreversible and network thermodynamics, and so on (plus the diverse work on relativistic quantum field theory and quantum gravity). Nor is the bearing of these researches straightforward. One particular focus is on renormalisation (cf. [Batterman, 2002]) to deal with critical point phase transitions. However, the treatment is characteristically indirect, e.g. renormalisation does not directly model the non-linear dynamics involved but rather offers an elaborate strategy, based on self-similarity achieved in an idealised limit, to side-step doing so while still arriving at the requisite end states (cf. [Belletti, *et al.*, 2009]). Within complex systems dynamics a general mathematical characterisation of chaos (strange attractor dynamics) has been developed. This has its own interest because it is related to the self-similarity of renormalisation, to work on irreversible non-linear semigroups as characterising coarse-grained models of chaotic dynamics, and because it presents a rare inherent realisation of randomness (to appropriate sampling) even though the motions themselves are deterministic. Again the interest is primarily intellectual, finitude making literal chaos of dubious practical importance. Near-to-chaos criticality, however, has been given important roles — see, e.g., [Van Orden, *et al.*, this volume], and this 'locational' role may be the most important one, cf. note 39. In sum, it may be the case that there are some general laws to be discovered in this way, and we may be driven in the direction of infinite 'particle' or 'node' limits to extract them by the impenetrability of quantum field theory. But given the diversity of dynamics skated over, whether it points beyond mathematical artifices and artifacts, and precisely how and why, remains to be made clear.<sup>92</sup>

The depth and breadth of mathematics required to cover all this is enormous. An elegant review [Holmes, 2005] of the history of abstract geometrical characterisation of the 'flows' produced by systems of differential equations reveals in passing the thicket of directly related domains. In closing it reveals the large range of more distinct domains not addressed. Though these studies yield a general characterisation of the stabilities and instabilities of flows and in particular their kinds of bifurcations, and we appreciate the diversity of application, much remains to investigate, e.g. which bifurcations are predictable, whether any have continuous dynamical descriptions, and diversity of applications for most. The upshot is that

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<sup>92</sup>For instance, Batterman [2002], in work deriving from renormalisation in condensed matter physics, holds that the structural universality in singular asymptotics represents the real basis of law-likeness (even generalised across networks of many kinds, cf. [Barabási, 2002; Poon and Andelman, 2006]). It is however unclear how general that work is, both because of the dynamical differences underpinning the asymptotics it spans (see [Hooker, 2004, section 3]) and because it still does not address global organisation and constraints (cf. [Hooker-c, this volume], note 18 and text).

there is relatively little communication among these various mathematical research domains. It may simply not be practically possible for any one person to be in a position to integrate these domains. And beyond this theoretical work there are more applied studies of individual complex systems dynamics of interest, now expanding very rapidly in virtually every science. Each of these studies involves its own skills and technical apparatus and is both dislocated from the foregoing theoretical work and every bit as internally diverse as it. Thus again it may not be practically possible for any one person to be in a position to integrate it. We are left then with a series of deep challenges to review and address.

#### 4.2.2 Chemistry

An immediate class of cases are those many non-linear irreversible systems like the Belousov-Zhabotinsky system that display emergent spatio-temporal structure, such as oscillations, and auto-catalytic systems that self-organise a transformed chemical constitution.<sup>93</sup> Similarly, biochemical reaction systems with multiple possible energetic outcomes, e.g. multiple reactant products or multiple protein folding options, typically provide multiple path-dependent dynamics and self-organised end states sensitive to initial spatial ordering conditions (cf. Hogeweg [2000a; 2000b], healthy and BCC-damaged brains being one prominent case). Complex molecules already pose challenges to simple ideas of handedness (besides ‘shoes’ showing simple left/right mirror asymmetries (chiralities), there are non-handed asymmetries or ‘potatoes’). They similarly challenge traditional notions of causality (since changes in molecular structure become a function of all participating chemical reactions).<sup>94</sup> As Ulanowicz [2003] remarks, becoming clear about all these matters is essential to understanding the chemical nature of life and its origins (cf. [Gánti, 2003; Bechtel, this volume]).

Beyond this, most chemical reactions are in practice irreversible thermodynamic processes, so currently defying analytical dynamical characterisation [Prigogine, 2003]. Moreover, chemical molecules are emergent dynamical structures, often with condition-dependent laws, e.g. as between various ionic forms of iron compound or forms of molecular symmetry. From this perspective, the whole of chemistry is a first ‘special science’ of complex systems beyond physics. Computational chemistry, where complex molecular reactions are digitally simulated, is now a cutting edge of chemistry and provides a wide variety of complex systems applications — see e.g. the review [Truhlar, 2008].

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<sup>93</sup>See e.g. [Bechtel, this volume; Golbeter, 1996; Gray and Scott 1994] along with Kauffman’s soups [Kauffman, 1993], Eigen’s hypercycles [Eigen and Schuster, 1979; Eigen and Winkler, 1993] and Haken’s synergetics [Haken, 1983; 1993].

<sup>94</sup>See e.g. and respectively, [King, 2003] and [Ulanowicz, 2003] from a special *Annals of the New York Academy of Science* devoted to foundations and philosophy of chemistry.



### 4.2.3 Geoscience

Geoscience gained a foundational dynamics of form with the adoption of plate tectonic dynamics and this has subsequently been complemented by a range of process dynamics of the materials involved: magma formation, sedimentation, metamorphosis and like chemo-physical formation and transformation dynamics, together with earthquake, weathering and like physical dynamics (e.g. [Aharonov and Sparks, 1999; Keilis-Borok and Soloviev, 2003]). Complex phenomena abound, e.g. the breakup of super-plates such as Gondwana represent dynamical bifurcations in plate tectonic dynamics, while various rock formation processes such as cracking represent series of phase shifts. As modelling of various process dynamics has grown more sophisticated, complex system dynamics has increasingly come to the fore. Multi-scale modelling has received rather more attention in geoscience than it has in other sciences, for instance, because of the grand spread of interacting process scales typically involved. Similarly, the role of unique events has received rather more attention in geoscience than it has in other sciences, for instance, because of the centrality of the path-dependent dynamics they yield, e.g. events occasioning particular tectonic plate fracturing patterns that determine its subsequent cracking, weathering and sliding properties.

Oreskes provides an examination of complex geoscience modelling, identifying many of the difficulties involved in their use. The general difficulties will be reviewed in section 5.2 below. In the light of her analyses she argues that such models may be confirmed but never validated and urges that they never be used to make long term predictions because these are invariably wrong and thus undermine respect for science and its role in public decision making.<sup>95</sup> This represents a major challenge to geoscience methodology and deserves examination.

In addition, idiosyncratic individuality has always been a problem to *geoscience* because of the scientific focus on discovering and applying simple general laws (compression, [Hooker-c, this volume]). Geo-logy, the universal laws of the earth, confronts the fact that the earth is a unique individual. That individual, like all living individuals, has a significantly idiosyncratic history that could have turned out rather differently had various component ‘chance’ events been different. This poses special methodological problems for geology: how does one investigate such an object, especially when the vast majority of its history is not directly accessible and feasible experiments cannot deal directly with the larger of its scales of operation? This issue has a close analogue in climate science (see [Snyder *et al.*, this volume]) and is analogous to investigating the developmental dynamics of societies and individuals in biology, where the same problems recur. How are these problems resolved and what is the impact on geo-science? Complex systems modelling provides the means to model idiosyncratic individuals through detailed model adjustment. Does this add distinctive methodological power (to the standard methods of multiple time sampling etc.) in geoscience? And, more widely, how has such modelling shifted the balance between evolutionary and complex sys-

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<sup>95</sup>See [Oreskes, 2000a; 2000b; 2003; 2007; Oreskes and Fleming, 2000].

tems ordering principles in understanding our planetary history (cf. the equivalent debate in biology, see [Hooker-b, 2009, section 6.2.3] below).

#### 4.2.4 *Engineering*

Engineering is so thoroughly suffused with non-linear dynamics and complex systems that to describe their characteristic presence is virtually to describe all engineering. From bridges and skyscrapers [civil and mechanical engineering] to electrical circuits [electrical and computer engineering] to pulp and paper mills and waste treatment plants [chemical and environmental engineering], even traffic flow dynamics [Schreckenberger and Wolf, 1998], all manifest complex non-linear dynamics. Even computers are in fact highly non-linear dynamical systems constrained so that their dynamical transitions model computation (sufficiently well). A simple electrical circuit with capacitors or inductances, e.g., is already a non-linear system and relatively simple versions of these form chaotic oscillators that show such features as sensitivity to initial conditions, strange attractors, rhythmic entrainment and phase change. Lingberg has studied the conditions that bring about chaotic dynamics in these circuits, with some instructive results.<sup>96</sup> Similar remarks could be repeated everywhere across engineering. Methods have had to follow suit. All feedback loops are dynamically non-linear, so control relationships are non-linear. But linear control theory, that is, the theory of the control of linear dynamical systems, formed into an elegant analytic theory 40 years ago (section 2 above). Non-linear control, including e.g. control of chaotic systems, however, is still developing its methods, with some general methods but often developing methods case by case, while controlled or guided self-organisation is also being developed.<sup>97</sup>

Recently engineering has noticeably expanded its models and methods towards the life sciences, even as the life sciences have moved toward it. First, particular methods were adopted and generalised from life sciences, e.g. neural network and genetic algorithm models used to model and control engineering systems, especially non-linear ones. Other examples among many are sensor network arrays that are intelligently organised and may mutually self-organise to perform complex functions and nano to micro insect-like molecular machines that perform designated functions, biomedical as well as industrial. Second, engineering methods were adopted by the life sciences, e.g. non-linear dynamical models of physiologies and ecologies and the spread of engineering design and dynamic control ideas and models into systems and synthetic biology. Systems and synthetic biology respectively aim to model cells and multi-cellular interaction as non-linear complex dynamical systems and to use such insights to design new artificial living systems.<sup>98</sup> These twin movements are allied to growing movements toward resiliently adaptable de-

<sup>96</sup>See e.g. [Cenys, 2003; Lindberg, 2004] and [http://server.oersted.dtu.dk/www/el/lindberg/el/public\\_html](http://server.oersted.dtu.dk/www/el/lindberg/el/public_html).

<sup>97</sup>See e.g. [Prokopenko, 2008] and the GSO-2008 conference at <http://www.prokopenko.net/gso.html>.

<sup>98</sup>See e.g. [Fu, *et al.*, 2009] and note 18 references.

signs for building lighting, energy use and other features, and similarly for traffic flows, industrial processing and so on. The advance of control engineering into all these areas, especially adaptive control of physiologies (e.g. pacemakers), societies of robots, ecologies and socio-economic systems, including warfare (cf. [Ryan, this volume]) completes the process of entanglement between the two domains.

All of these developments are now in their infancy and are set to gather pace. Together they will eventually radically transform both engineering and the life sciences, ushering us into the long-anticipated Cyborg Era. Here there will arise many important scientific issues, e.g. how to develop improved participatory self-control processes for social groups (human and socially active robots) so that control of their own social systems may develop, including self-organise. (This issue has already arisen within organisational management.) There will also arise foundational/philosophy of science issues concerning the limits of engineering modelling, problems of predictability and anticipatory control, and the like. And beyond these issues, this merging of scientific disciplines and practices will raise (has already raised) deep existential, ethical and social issues that will deserve close study.

#### 4.2.5 *Neurophysiology/Neuropsychology/Psychophysiology*

Science has been investigating neurons for 120 years, but useful dynamical models for networks of them are less than half that age. At that time we were entering the computer age and cognitive psychology was captured by abstract functionalism that was morphing from late behaviourism into computationalism. Behaviourism is a form of the input-output analysis common in engineering. Input-output analysis will always be applicable<sup>99</sup>, but the only internal structure it can attribute to the modelled object is what can be introjected from external correlations among inputs and outputs (called intervening variables in Behaviourism). Behaviourism had the potential to expand into internal (neural) dynamical modelling and control, as engineering modelling has done. Unfortunately, this was blocked by its own positivist ideology ('there is no inside'), and then the shift to internal computer science models emphasised purely logically based architecture that was independent of implementation, cutting off neural modelling. (Computing devices could implement minds, so also could millions of people passing paper bit strings among themselves in the right ways.) Cognition was then normatively determined by its functional logical structure, everything else was simply implemented performance. Neurophysiology and beginning complex system dynamical modelling of neural

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<sup>99</sup>Indeed, methodologically there is always a tension between achieving adequate internal modelling and employing a more agnostic and pragmatic approach that advocates use of simple standard models, like Kalman filters, whilst ever they work in practice, = for the input-output form of the original problem. Rather like (possibly exactly like in situ) behaviourism's intervening variables, these models often work as well or better than attempts at more realistic internal dynamical modelling, e.g. to discover patterns in sparse, high dimensional data and where there simply are no dynamical models available. See further the discussion of Breiman's similar argument at section 6.2.5 below that broadens the issue to machine learning generally.

systems progressed steadily during this time, but was held logically irrelevant to understanding cognition itself. (It was potentially useful in understanding practical performance competencies or malfunctions.) For its part, neurophysiologists were swamped with detailed data for which, with some exceptions (e.g. the discovery of visual edge detectors), it was impossible to see through the welter of detail to their cognitive significance.

Philosophy had no trouble following suit in all this since the rational mind as logic machine had long been dominant and was much easier than behaviourism to translate into computational terms. Its purest form was that of Putnam's early Turing machine functionalism,<sup>100</sup> extending from there into a general logical computational functionalism. This remains the dominant view and explains why cognitive philosophers, with rare exceptions (e.g. [Port and van Gelder, 1995]), have paid no attention to dynamical models or complex systems (cf. [Elias-Smith, 2009a]).

That era is now drawing to a close. A first step was the 1980's revival of Rosenblatt's 1950's perceptron in a generalised form that now contained one or more 'hidden' layers between the input and output layers, so-called 'neural nets'.<sup>101</sup> The essence of these non-linear models was their power to extract high-order patterns from complex data when it was difficult or impossible for humans to do so. The relevant point here is that the secret of their success was sub-categorical processing: they process information and store it in their internal ('hidden') layers in terms of non-logical (typically mathematical) functions of the input and output components and, in cognitive cases, in terms of non-logical functions of the input and output categories. In this way their hidden layers can represent information that cannot be expressed as any logical combination of inputs and outputs, and hence the output classification is not arrived at from the input by any process of purely logical analysis.<sup>102</sup> It shows that the underlying processes, invisible to everyday cognition, may be crucial to cognitive capacities and not simply affect the imple-

<sup>100</sup>See e.g. [Putnam, 1975], cf. [Coltheart, 2006a]. Turing machines are the structurally simplest universal computers, that is, in principle able to compute all computable functions. For the sake of intellectual propriety we should note immediately that (i) 'in principle' here is sweepingly abstract, it includes very many computations that could not be carried out in any material universe of our kind (cf. [Cherniak, 1986]) and (ii) mathematics, and so science, has many non-computable functions (see e.g. [PourEl and Richards, 1989; Shipman 1992] and [http://wopedia.mobi/en/Church-Turing\\_thesis?t=9](http://wopedia.mobi/en/Church-Turing_thesis?t=9)). These points appear simultaneously as demonstrations of the power of abstract thought and caveats concerning the reach of computation. To pursue them further, e.g. into undecidable and incomplete formal systems and Gödel-style computational models, is beyond this book's focus.

<sup>101</sup>The original perceptron was a two-layer input-output filter (classifier) adapted through supervised learning (that is, where errors produced on an initial input-output training set are fed back to modify the inter-layer relationships (here linear weights)). This proved too simple to learn many classifications, which damped further research until the 'hidden' layer versions were shown to perform much better. See e.g. <http://en.wikipedia.org/wiki/Perceptron> references.

<sup>102</sup>For this reason Smolensky [1988, pp. 3-9] said they were operating in a sub-conceptual, sub-symbolic mode, but not yet the mode of dynamics proper. He labelled this a half-way level between symbolic and dynamic, but this runs together different notions [Hooker, 1995a, note 10]. See e.g. [Rummelhart and McClelland, 1986] and [Hooker, 1995a] for critical review and references.

mented performance of capacities already determined by logical structure. This is a first step away from conceptual computation as the basis of cognition and toward more generalised dynamical models.

A further step in this direction is inherent in the shift from node-focused neural net functions to a focus on dynamical states themselves. It is possible, e.g., to achieve substantial reduction in size for fault-tolerant networks by exploiting dynamical redundancy or degeneracy rather than the traditional node/connection redundancy (which increases network size).<sup>103</sup> To the extent that neuronal systems behaved in this way there would be a gain in economy (less nodes) and in resilience (fault-tolerance), both evolutionarily advantageous features. But understanding them would shift further away from any simple logical structure as foundational and decisively toward dynamically-based discriminations as the basis for agent-integrated functional capacities. This is the kind of step that has been recently taken by the embodied functionality movement within robotics — section 4.1.1 above. However, it remains an open challenge to really bring embodied robotics into a deep relationship to current brain-modelling inspired neuropsychology (cf. also section 4.2.6 below). On the other hand, that step away from symbolic computational models is reinforced by the emphasis of [Van Orden, *et al.*, this volume, section 3.2] on the self-organised resolution of near-to-chaos criticality as a decision making/solving process and on the ‘soft-assembly’ (temporary self-organisation) of task-specific neural devices as intentional action preparation.

Although neuron-like only in their interconnectedness, ‘neural nets’ do form the first non-linear dynamical models to have significant cognitive application. Their advent also generated the first real philosophical revolt from computational functionalism. Churchland [1989; 1995] adopted these models to argue for a more conceptually liberated, more empirically connected philosophy of mind. It is still worth reading to understand the fault and flow lines of the philosophical and scientific shift still underway. However, today we know that neural nets form one class of learning machines, others include classification and regression trees and kernel-based learning machines, including support vector machines. Although applications, sometimes of combinations of these, are expanding rapidly, these methods have yet to be fully integrated with scientific practice and are themselves still developing.<sup>104</sup> These developments have created the rich domain of machine learning and statistical inference. This is a diverse and rapidly expanding domain of artificial learning processes, no longer explicitly tied to brain modelling and new

<sup>103</sup>[Penfold, *et al.*, 1993], e.g., reports success in generating fault-tolerant networks for the XOR function (= exclusive ‘or’, aXORb = either a or b but not a and b) using a genetic algorithm and training selection. XOR has been considered a standard test for non-trivial functional capacity since it was shown that a (1-layer) perceptron could not learn the function. The fault-tolerant networks generated were half the size of the best node redundancy versions. This derived from that fact they were able to cycle through their state space and always settle into an XOR-able attractor after a time, despite the removal of a node and its connections. Cf. [Kohlmorgan, *et al.*, 1999; Zhou and Chen, 2003].

<sup>104</sup>See, e.g., [Hastie, *et al.*, 2008; Tan, *et al.*, 2006; Vapnik, 2001]. Neural nets may prove to have distinctive roles in control, and possibly in nervous system regulation, but this remains to be seen — see [Hooker-b, this volume, section 6.2.5].

for psychology. A key part of the Cyborg Era (4.2.4 above), how does this domain of new techniques relate to nervous system function and to its cognitive capacities and performance?

Today, non-linear dynamical models of the brain abound and there are ever-tightening interrelations between neurophysiology and cognitive psychology, their union encapsulated in ‘neuropsychology’ and like labels. This revolution has been largely brought about by new technologies for investigating brain function (cf. e.g. [Bressler and Kelso, 2001]), especially patterns of neuron firing and detailed anatomical tracing of neural pathways. To this is now added various forms of neurological imaging, e.g. functional magnetic resonance imaging. The earlier position is analogous to that of cell biology before the contemporary high throughput technologies that now provide the ‘-omics’ data: in each case, though non-linear dynamical models of their respective components have been developed, it is very difficult to construct even roughly realistic complex systems models of their collective functioning.

However, even were that to be accomplished it would still be distant from the high-order functional descriptions that psychology employs. (Would it be analogous to high-order cell and multi-cellular physiology?). Neuronal firings may self-organise into systematic and complex patterns across the brain, but understanding how that might support cognitive or other functions is another matter. Coltheart [2006a; 2006b], for instance, has argued that neuro-imaging has contributed little constructive to cognitive psychology and much that is distracting or misleading (cf. [Elias-Smith, 2009b]). This is essentially because there are mostly no one-one neural-(cognitive)functional correlations to be discovered. The brain evidently employs ubiquitous multi-plexing and multi-tasking, with emergent (perhaps self-organised) constraints on these shifting on several timescales (cf. [Griffiths and Stotz, 2007] for genes). As with even simple machines of these kinds, this means that any high-order functional capacities to which psychology may appeal will be multiply neurally realised in condition-dependent ways. Conversely, the reverse engineering problem of identifying the psychology from the dynamics (much less from current neuroimaging) will prove essentially impenetrable until it is understood what are the dynamical principles on which the multi-plexing and multi-tasking are organised.

Are cognitively significant aspects of brain processes coordinated to larger scale, and/or longer process times, as emergent spiking dynamics might suggest (cf. [Elias-Smith, 2000; Port and van Gelder, 1995])? Is there a point in higher order neural function beyond which functional organisation is completely or mostly determined by the requirements of effective logical problem solving? (I suspect not, on the grounds that [Van Orden, *et al.*, this volume] provide, and because SDAL processes — 4.1.3 above — apply to the most advanced problems.) Such issues, allied to the current diversity of neuropsychological models of brain functional organisation, all claiming to capture the truth, points to the need to resolve the issue of proper methodology for neuropsychology and the place of neuro-imaging and like technologies within it. This is in turn a challenge shared with virtually every

other domain of current complex systems investigation (see further [Hooker-b, this volume]).

This latter challenge is itself part of a larger task of insightfully interrelating work on neural networks, more physically oriented brain models and agent based social network models. In all of these classes of non-linear dynamical networks we discover certain phenomena, e.g. emergent collective dynamics and ‘small worlds’ hub-and-spoke structures. But how these are to be understood in each class may be different. Any network modelling faces the issue of determining to what extent the network dynamics is dominated by node capacities and to what extent it is dominated by connection structure (net topology) and connection strength and operational character. For boolean and adaptive neural nets, e.g., the node capacities are extremely limited (usually just summation or saturating summation) and the connection strengths are either constant (boolean) or simple functions of node values (adaptive neural) and no other operating constraints are applied. Again, many brain neuron net models concern spike timing only, throwing away all internal neural information. But neurons have much more complex non-linear axon dynamics than this (indeed, axon protein is said to possess vast computational power) and synaptic firing involves complex chemical transfers. It would, e.g., be instructive to use modelling tools to explore these interrelationships. (For instance, to generalise a tool like MARVEL that enables staged addition of physical features to abstract network models, see [van Zijderveld, 2007].) And while many social agent based models accord their human agents only simple capacities (e.g. a few independent, first order interaction rules), human agents possess autonomy-based independent evaluation and the capacity to form many highly context-dependent, long range and idiosyncratic relationships that can nonetheless have a powerful effect on the net dynamics. Agent rules simple enough to capture the dominant aspects of insect and bird swarming are unlikely to be able to illuminate any but the grossest aspects of the dynamics of scientific research or large scale project management networks. We have as yet scarcely crossed the threshold of understanding our new complex system modelling tools.

From the philosophical side there is an ongoing debate between those who take a reductionist approach to neuropsychological relations and those who adopt a mechanistic approach with more complex unification.<sup>105</sup> Both sides focus on much the same neurophysiological domains, long term potentiation/conditioning and memory, to provide evidence for their position. Especially if one takes on board the dual interrelations of emergence and reduction [Hooker-c, this volume], it is not clear that there need be any absolute opposition between these approaches (as opposed to the philosophical terms in which they are sometimes stated) — see [Hooker-b, this volume, section 6.2.3]. However Sullivan [2009], after examining in detail the experimental designs and protocols underlying these opposing claims, argues that there is such diversity among the protocols involved across current neuroscience that no conclusions either way can yet be drawn. This is not an unusual position for the investigation of any class of complex systems to find itself

<sup>105</sup>See, e.g., and respectively [Bickle, 2003; 2006; Churchland, 1986] and [Craver, 2002; 2007].

in today and reflects both the inherent methodological complexities involved and the early stage of methodological development. Sullivan concludes that the entire experimental domain requires a more careful and detailed analysis and she offers some new investigative directions for the philosophy of neuroscience. The future challenge is to develop a mature investigative methodology and to resolve how neuropsychology and cognate fields are to be philosophically understood.

These studies hook up in a natural manner with those starting from a more traditional psychological base but with theorising enlivened with complex systems ideas, such as [Smith and Sheya, this volume] and [Van Orden, *et al.*, this volume]. To these excellent introductions to a rich field I wish only to point to complementary work, such as that on emotional development, especially emotional self-regulation (see e.g. [Fogel, *et al.*, 2008; Lewis, 2005; Lewis and Todd, 2007; Lewis and Cook, 2007]). To this I add work applying ideas of developmental self-organisation, as well as less dramatic approaches using dynamical models, to identify specific processes [Heath, 2000; Ward, 2002] and dynamical modelling of individual patients as support for clinical treatment (e.g. [Heiby, *et al.*, 2003]), a new capacity afforded by parametric adjustment of the preceding dynamical models.

#### 4.2.6 *Social science*

The recent explosive development of synthetic and systems biology is fuelled by the adaptation of complex systems models from chemical and electrical (especially control) engineering. This tactic works because for many purposes intra-cellular components can be treated as simple deterministic systems and the complexity located in their many organised interrelations. The tactic fails when it comes to modelling social systems because the components, persons, are themselves (extremely) complex systems. Economists faced this issue long before complex systems approaches became readily available. Their response was mainly to assume a universally representative ideal rational agent and to use its rationally deterministic behaviour as a surrogate for aggregate behaviour. Later they allowed for a more explicit averaging process, but with random behavioural variation and an emphasis on strong aggregation rules in the limit of large numbers (central limit theorems), to again extract representative aggregate outcomes, in analogy to statistical physics [Auyang, 1998]. The development of Traditional Game Theory relieved the constraints of simple determinism and collective uniformity by introducing a limited variety among players (namely variety in utility of outcomes) and a correlative capacity to discriminate among strategies. This still represents only limited relief, but even this much generates very rich modelling capacities (see e.g. [Harms, this volume]).

The relief is importantly limited because (I) persons have the capacities to construct complex internal models of both (i) their environment and their options within it and (ii) themselves and others in respect of their beliefs, motivations, values and limitations. In consequence, (iii) they take up complex and idiosyn-



cratic strategic relationships (trading, research collaboration, villification, ...) with specific individuals both near and socially distant. Moreover, (II), they operate within a social milieu whose expectations vary from highly specific to vaguely wide and whose structure varies from highly labile to recalcitrantly entrenched (cf. 4.1.2 *Cultural dynamics* above). In consequence, people can interact (a) even when they have incompatible models of the game being played, (b) when they are simultaneously playing strategies within and about a game<sup>106</sup>, and (c) when they are part, intentionally or not, of transforming the rules under which the primary game is being played (an important purpose of politics and like social regulation). In a social setting, e.g., often the most intelligent response to a Prisoner's Dilemma game (see [Harms, this volume]) is to seek to change the terms of the game. Modern economic institutions, for instance futures markets, can all be traced to particular historical innovations, they are not timeless features of our inherent rationality or social landscape. On this latter score, the relief offered by Traditional Game Theory is also limited because it represents games and strategies timelessly, their responses to others' moves simply a set of quasi-logical possibilities, whereas in real life timing may be everything.<sup>107</sup> Here the recent shift, more monumental than it may appear on the surface, from Traditional Game Theory to Dynamic Game Theory (let us call it), greatly expanded its capacity to represent strategies as sequentially distributed, with consequent increased representational richness and some surprising, and telling, outcomes (see e.g. [Harms, this volume]).

These developments are complemented by the introduction of ecological mod-

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<sup>106</sup>See, e.g., Rapoport's wincingly poignant analysis of Othello and Desdemona as in fact playing different, incompatible games, even while each assumes that the other is also playing their game [Rapoport, 1966]. Here innocent Desdemona's perspective leads her to represent her situation in a game in which Othello is assumed to share her moral values and has as his dominant strategy believing her innocent, to which her best response is to affirm her innocence. (This is best, rather than falsely admitting guilt in the hope of a pardon, a response also of inferior expected utility so long as the probability of Othello's belief in her innocence is greater than .5.) But Othello's suspicion of her (whether based on the vice of paranoia or the virtue of respect for a fellow officer's advice) insures that his representation of their situation is expressed in a game where he and Desdemona do not share the same values and she has a dominant deception strategy to which his tragic best response is to believe her guilty. Here differences in judgement between Othello and Desdemona lead, not just to differences of game detail, such as in outcome utilities, nor even to differently available strategies within a game, but to divergent forms of the game they take themselves to be playing. Whether or not to believe Desdemona as an issue of strategy choice within a game is quite different from, though subtly related to, whether or not to believe her as part of conceptualising the decision problem itself. This situation also underlines the often crucial role of communication in social decision making (contrast Othello's attitude to communication with that of Desdemona, and that of Iago). Though in Othello's case lack of communication had disastrous results, there are other situations where the inability to communicate improves the rationally accessible outcome, e.g. by removing the capacity to threaten or bluff and the like (e.g. [Rapoport, 1966, pp.126-7]). In sum, here we uncover a recurring theme in social process: rationality cannot consist simply in the formal playing out of specific games but is more fundamentally to do with the management of one's non-formal judgements of oneself and others that underlie formal game form itself.

<sup>107</sup>The 'meta-game', introduced by [Howard, 1971], that considers an extended game of several plays of an original game, can be analytically useful, but is still represented as timeless possibilities. (Note: a meta-game is not a supra-game about playing another game.)

elling (e.g. [Holland, 1995]) and the rise of social robotic agents (see [Nolfi, this volume]). Together they reinforce the contemporary shift toward the less structured and hence less confined agent-based network models now sweeping computational modelling in the social sciences (e.g. [Epstein, 2007; Ferber, 1999; Sawyer, 2005]). Cellular Automata models, employing local neighbour-neighbour interaction rules were among their earliest and best developed kinds (see [Wolfram, 2002]). Typically still focused around local interaction rules, these models follow the development of the interacting community over successive interactions (see also both [Lansing, this volume] and [Green and Leishman, this volume]). There is now a vast and rapidly expanding research literature, studying everything from group dynamics to institutional rule emergence, to macroeconomics. It is supported by international research institutions (societies, conferences, journals), and already with sufficient development to bring the social and robotics modellers together.<sup>108</sup> Here is the context where the self-organised emergence of social institutions is natural rather than unrepresentable (see section 5.3 below), where economics can be re-configured without the restriction to artificially rational, self-interested agents [Foster, this volume] and where the rules of science (distributive, constitutional and aggregative) can emerge from strategic actions by scientists instead of being eternally fixed ([Shi, 2001], see section 4.1.3 above).

Promising as this young field is, there is also a danger that this kind of social modelling is ‘too easy’. Almost anything can be ‘modelled’ by throwing in some simple interaction rules and generating the usual slew of collective pattern features (cf. [McKelvey, 1999]). This runs the risk of undermining its insightfulness. Nonetheless, all the same methodological issues and criteria for sound procedure apply here as they do elsewhere. ([Goldspink, 2002], e.g., provides a nice review.) Increasing domain maturity will only winnow its products and improve its quality. However, as [Harms, this volume] argues, unless and until the self-organisation of social structure can be harnessed in explanatorily adequate ways there will remain a place for the multi-layered models he describes. Certainly, many are currently seeing much promise in a generalised ‘network science’ (cf. [Barabási and Bonabeau, 2003; Strogatz, 2001; Green, this volume]), an inheritor of the General Systems Theory mantle [Hofkirchner and Schafranek, this volume] that promised a trans-disciplinary systems framework for all sciences. This last has in recent times principally been prompted by the ubiquity of the ‘small worlds’ phenomenon, where most interconnections run through a few common nodes, greatly reducing node-node interaction distances [Barabási and Bonabeau, 2003]. When nodes are persons or groups of persons, this offers a richer, wider representation of asymmetrical interrelations than traditional tools like power hierarchies, and one with a more clearly underlying dynamical character. Because reducing interaction

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<sup>108</sup>See generally e.g. [Antunes and Takadama, 2007; Epstein, 2007; Ferber, 1999] and e.g. <http://emil.istc.cnr.it/publications/>. On bringing together social and robotics social simulation see e.g. the First IJCAI Workshop on Social Simulation, <http://ss-ijcai2009.di.fc.ul.pt/>, during the 21st International Joint Conference on Artificial Intelligence, IJCAI-09, <http://ijcai-09.org/>.

distance can be represented as a form of economy or efficiency, the dynamics can be generalised to many other non-social applications.

Yet we should not hasten to suppose that any one simple pattern formation process captures all the complexities of social life. First, we should also recall that, as an exercise of power, those same common nodes can block interrelations as easily as facilitate them, e.g. block or bias communication (censorship, research domination, ...). To this we should add, second, that small world dynamics is by no means universally fixed. The internet, for instance, by vastly shortening communication interaction, allows a much richer plethora of partial small worlds to form and dissolve. By contrast, many other situations are characterised by long range and idiosyncratic relationships that can nonetheless have a powerful effect on the net dynamics, e.g. scientific research interactions (cf. Section 4.1.3, penultimate paragraph, and 4.2.5 above). Third, because networks are defined by none-node relations, especially if confined to local neighbourhood relations, they are as ill-equipped to represent organisation and global constraints as is phase space dynamics (section 5.1.1, [Hooker-b, this volume]). Thus it is but a tempting mistake to suppose that a city, business firm or research laboratory is simply a small world. They are small worlds, but that does not distinguish them from neighbourhood barbecues and internet twitters. In fact these entities possess significant autonomy and are no more merely small worlds than are biological organisms. Indeed, fourth, the appearance of small worlds phenomena might reflect no more than the limitations of agent finitude, here expressed in the number of connections that can be successfully maintained. Insofar as this is akin to the attention constraint to  $7 \pm 2$  bits [Miller, 1956], it too is independent of subject matter and therefore offers no specific illumination (cf. [Fox Keller, 2005]).

Minimising interaction distance is attractive for finite agents and finitude is a powerful, many-sided constraint. As finite agents, persons are typically overwhelmed with the complexity of potential social interaction and sensibly seek ways to simplify their deliberations and decision making. This is accomplished primarily through the creation of shared expectation-setting social structure, simplified agent models (e.g. personality/ propensity profiles: irritable, generous, ...) and the use of simplified 'good enough' rational procedures ('rules of thumb', satisficing — see [Simon, 1947; 1969; Foster, this volume]), correcting these locally only when problems arise. Agent based modelling with finitude, especially satisficing, constraints is also thriving in social simulation (see, e.g. [Brock and Hommes, 1998; Hommes, 2001] on heterogeneous agents and bounded rationality). On the other hand, in focusing on this aspect, we should again not pre-emptively restrict agent social interaction capacities: the same finite agents that will use cheap and dirty heuristics to engage in Rapoport's fights and play Rapoport's games are also capable of the sensitive, flexible and rationally creative and constructive interaction called for by Rapoport's debates (see [Rapoport, 1970]). Whether and how all the human social richness will find its place in social simulation remains open, a huge and interesting challenge for future dynamical modelling — and in robotics as well (to add to their autonomy challenge, see 4.1.1 *Autonomy* and section 4.2.5 above).

## ACKNOWLEDGMENTS

This essay and its closing companion essay have especially benefited from constructive comment on an earlier draft by Bill Bechtel, Mark Bickhard, Thomas Brinsmead, David Green, Jan Schmidt and Olaf Wolkenhauer. I am grateful for their substantial efforts, and to several other authors for particular helpful remarks. Above all I am grateful to my wife Jean whose practical generosity amid her own obligations made a long, time-consuming task so much easier and whose love enlightens everything.

## BIBLIOGRAPHY

- [Aharanov and Sparks, 1999] E. F. Aharanov and D. Sparks. Rigidity phase transition in granular packings. *Physical Review E*, 60, 68906896, 1999.
- [Ahouse, 1998] J.C. Ahouse. The tragedy of apriori selectionism: Dennett and Gould on adaptationism. *Biology and Philosophy*, 133, 359-91, 1998.
- [Ahouse and Berwick, 1998] J. C. Ahouse, R. C. Berwick. Darwin on the Mind. *Boston Review*, 23, 36-41, 1998.
- [Andersen *et al.*, 2000] P. B. Andersen, P. V. Christiansen, C. Emmeche, N. O. Finnemann (eds.), *Downward Causation: Minds, Bodies, and Matter*, Aarhus University Press, Aarhus, 2000.
- [Anderson, 1972] P.W. Anderson. More is different: broken symmetry and the nature of the hierarchical structure of science. *Science*, 177, 393-396, 1972. Reprinted in [Bedau and Humphries, 2008], pp. 221-230, 1008.
- [Anderson *et al.*, 1988] P. W. Anderson, K. J. Arrow, D. Pines (eds.). *The economy as an evolving complex system*. Addison Wesley, Redwood City, Cal., 1998.
- [Antunes and Takadama, 2007] L. Antunes and K. Takadama. (eds.). *MultiAgentBased Simulation VII*, Lecture Notes in Artificial Intelligence. Springer, Berlin, 2007.
- [Arthur *et al.*, 1997] W. B. Arthur, S. N. Durlauf, D. A. Lane. *The economy as an evolving complex system II*, Addison-Wesley, Reading MA, 1997.
- [Ashby, 1947] W. R. Ashby. Principles of the SelfOrganizing Dynamic System. *Journal of General Psychology*, 37, 125-128, 1947. Also in H. Von Foerster and G. W. Zopf, Jr. (eds.), Principles of SelfOrganization, Pergamon, New York; republished in *Emergence: Complexity and Organization* (E:CO), 6(12), 1021-26, 2004.
- [Ashby, 1952] W. R. Ashby. *Design for a Brain*. Chapman & Hall, London, 1952.
- [Aunger, 2000] R. Aunger (ed.). *Darwinizing Culture: The State of Memetics as a Science*. Oxford University Press, Oxford, 2000.
- [Auyang, 1998] S. Y. Auyang. *Foundations of complex systems theories in economics, biology and statistical physics*. Cambridge University Press, Cambridge, 1998.
- [Axelrod, 1997] R. Axelrod. Advancing the art of simulation in the social sciences. *Complexity*, 3(2), 16- 22, 1997.
- [Barabási, 2002] A.-L. Barabási. *Linked: the new science of networks*. Perseus Books, Cambridge, 2002.
- [Barabási and Bonabeau, 2003] A.-L. Barabási and E. Bonabeau. Scale-free networks. *Scientific American*, 288(May), 50-59, 2003.
- [Barandiaran and Moreno, 2008] X. Barandiaran and A. Moreno. Adaptivity: from metabolism to behavior. *Adaptive Behavior*, 16(5), 325-344, 2008.
- [Barandiaran and Ruiz-Mirazo, 2008] X. Barandiaran and K. Ruiz-Mirazo, eds. *Modelling autonomy: simulating the essence of life and cognition*. *BioSystems*, 91(2), 2008.
- [Batterman, 2002] R.W. Batterman. *The devil in the details: asymptotic reasoning in explanation, reduction and emergence*. MIT Press, Cambridge, Mass., 2002.

- [Bechtel, 1989] W. Bechtel. An evolutionary perspective on the re-emergence of cell biology. In [Hahlweg and Hooker, 1989b], pp. 433-457, 1989.
- [Bechtel, 2007] W. Bechtel. Biological mechanisms: organised to maintain autonomy. In [Boogerd, *et al.*, 2007], pp. 269-302, 2007.
- [Bechtel and Richardson, 1993] W. Bechtel, R. Richardson. *Discovering complexity*. Princeton University Press, Princeton, 1993.
- [Bedau, 1997] M. A. Bedau. Weak emergence. In J. Toberlin (ed.), *Philosophical perspectives: mind, causation and world*. Blackwell, Oxford, 375-399, 1997.
- [Bedau, 2007] M. A. Bedau. What is life? In S. Sarkar, A. Plutynski (eds.), *A Companion to the Philosophy of Biology*. Blackwell, New York, 455-471, 2007.
- [Bedau and Humphries, 2008] M. Bedau and P. Humphries (eds.), *Emergence: contemporary readings in philosophy and science*, Bradford/MIT Press, Cambridge, Mass., 2008.
- [Beer *et al.*, 1993] R. D. Beer, R. E. Ritzmann, T. McKenna (eds.). *Biological neural networks in invertebrate neuroethology and robotics*. Academic Press, New York, 1993.
- [Beer, 1972] S. Beer. *The brain of the firm*. Allen Lane, The Penguin Press, London, 1972.
- [Beer, 1979] S. Beer. *The heart of the enterprise*. John Wiley, New York, 1979.
- [Behe, 2000] M. J. Behe. Self-organization and irreducibly complex systems: a reply to Shanks and Joplin. *Philosophy of Science*, 67, 155-162, 2000.
- [Belletti *et al.*, 2009] F. Belletti, A. Cruz, L. A. Fernandez, A. GordilloGuerrero, M. Guidetti, A. Maiorano, F. Mantovani, E. Marinari, V. MartinMayor, J. Monforte, A. Muñoz Sudupe, D. Navarro, G. Parisi, S. PerezGavero, J. J. RuizLorenzo, S. F. Schifano, D. Sciretti, A. Tarancon, R. Tripiccion, D. Yllanes. An InDepth View of the Microscopic Dynamics of Ising Spin Glasses at Fixed Temperature. *Journal of Statistical Physics*, 135(56), 1121-1158, 2009.
- [Bennett, 1985] C. Bennett. Dissipation, information, computational complexity and the definition of organization. In [Pines, 1985], 1985.
- [Bennett, 1992] C. Bennett. Logical depth and other algorithmically defined properties of finite objects. *Proceedings, Workshop on Physics and Computation*, IEEE, 75-77, 1992.
- [Bennett, 1986] S. Bennett. *A history of control engineering, 1800-1930*. Peregrinus/ Institution of Electrical Engineers, London, 1986 (1<sup>st</sup> edn, 1979).
- [Bennett, 1993] S. Bennett. *A history of control engineering, 1930-1955*. Peregrinus/ Institution of Electrical Engineers, London, 1993.
- [Bickhard, 1993] M. Bickhard. Representational content in humans and machines. *Journal of Experimental and Theoretical Artificial Intelligence*, 5, 285-333, 1993.
- [Bickhard, 2000a] M.H. Bickhard. Emergence. In [Andersen, *et al.*, 2000], pp. 322-348, 2000.
- [Bickhard, 2000b] M.H. Bickhard. Autonomy, function, and representation. In A. Etchebberia, A. Moreno, J. Umerez (eds.), *The contribution of artificial life and the sciences of complexity to the understanding of autonomous systems*, *Communication and Cognition*, Special Edn, 173-4, 111-131, 2000.
- [Bickhard, 2001] M.H. Bickhard. Error dynamics: the dynamic emergence of error avoidance and error vicariants. *Journal of Experimental and Theoretical Artificial Intelligence*, 13, 199-209, 2001.
- [Bickhard, 2002] M.H. Bickhard. Critical principles: on the negative side of rationality. *New Ideas in Psychology*, 20, 1-34, 2002.
- [Bickhard, 2005] M.H. Bickhard. Interactivism: a manifesto. At <http://www.lehigh.edu/~mhb0/>.
- [Bickhard, 2008] M.H. Bickhard. *The Whole Person: toward a naturalism of persons*. At <http://www.lehigh.edu/~mhb0/>.
- [Bickhard and Terveen, 1995] M. Bickhard, L. Terveen. *Foundational issues in artificial intelligence and cognitive science: impasse and solution*. Elsevier, Amsterdam, 1995.
- [Bickle, 2003] J. Bickle. *Philosophy and neuroscience: a ruthlessly reductive account*. Kluwer, Boston, 2003.
- [Bickle, 2006] J. Bickle. Reducing mind to molecular pathways: explicating the reductionism implicit in current cellular and molecular neuroscience. *Synthese*, 151, 411-434, 2006.
- [Blackmore, 1999] S. Blackmore. *The Meme Machine*. Oxford University Press, Oxford, 1999.
- [Blake *et al.*, 1960] R. M. Blake, C. J. Ducasse, E. H. Madden. *Theories of scientific method*. University of Washington Press, Seattle, 1960.
- [Bloch, 2003] A.M. Bloch. *Nonholonomic mechanics and control*. Springer, New York, 2003. See [http://www.cds.caltech.edu/mechanics\\_and\\_control/about\\_this\\_book/](http://www.cds.caltech.edu/mechanics_and_control/about_this_book/) for corrections and additions, incl. internet supplement.

- [Blume and Durlauf, 2006] S. N. Durlauf. *The economy as an evolving complex system III*, Oxford University Press, Oxford, 2006.
- [Boccaletti *et al.*, 2006] S. Boccaletti, V. Latora, Y. Moreno, M. Chavez, D. U. Hwang. Complex networks: structure and dynamics. *Physics Reports*, 424, 175-308, 2006.
- [Boogerd *et al.*, 2002] F. C. Boogerd, F. J., Bruggeman, C. Jonker, H. L. De Jong, A. Tamminga, J. Treur, H. V. Westerhoff, W. Wijngaards. Interlevel relations in computer science, biology, and psychology. *Philosophical Psychology*, 15(4), 463-472, 2002.
- [Boogerd *et al.*, 2005] F. C. Boogerd, F. J., Bruggeman, R. C. Richardson, A. Stephan, H. V. Westerhoff. Emergence and its place in nature; a case study of biochemical networks. *Synthese* 145, 131-164, 2005.
- [Boogerd *et al.*, 2007] F. Boogerd, F. Bruggeman, J-H. Hofmeyr, H. V. Westerhoff (eds.), *Systems Biology: Philosophical Foundations*, Amsterdam, Elsevier, 2007.
- [Brading and Castellani, 2003] K. Brading and E. Castellani, eds. *Symmetries in physics: philosophical reflections*. Cambridge University Press, Cambridge, 2003.
- [Braitenberg, 1984] V. Braitenberg. *Vehicles: experiments in synthetic psychology*. MIT Press, Cambridge MA, 1984.
- [Bressler and Kelso, 2001] S. L. Bressler and S. Kelso. Cortical coordination dynamics and cognition. *Trends in Cognitive Sciences*, 5(1), 26-36, 2001.
- [Brinsmead and Hooker, 2005] T. S. Brinsmead and C. A. Hooker. *Sustainability: a systematic framework and comparative analysis*, Research Report 53. Cooperative Research Centre for Coal in Sustainable Development, Brisbane, (pp.113), 2005.
- [Brock and Hommes, 1998] W. A. Brock and C. H. Hommes. Heterogeneous beliefs and bifurcation routes to chaos in a simple asset pricing model. *Journal of Economic Dynamics and Control*, 22, 1235-1274, 1998.
- [Bronowski, 1965] J. Bronowski. *The identity of man*. Heinemann, London, 1965.
- [Brooks, 1991] R. A. Brooks. Intelligence without representation. *Artificial Intelligence* 47, 139-159, 1991.
- [Brown and Harré, 1988] H. R. Brown and R. Harré (eds.). *Philosophical foundations of quantum field theory*. Clarendon Press, Oxford, 1988.
- [Bruggeman *et al.*, 2002] F. J. Bruggeman, H. V. Westerhoff, and F. C. Boogerd. BioComplexity: A pluralist research strategy is necessary for a mechanistic explanation of the 'live' state. *Philosophical Psychology*, 15(4), 411 — 440, 2002.
- [Campbell, 1974a] D. T. Campbell. Downward causation in hierarchically organised biological systems. In F. J. Ayala, T. Dobzhansky (eds.), *Studies in the philosophy of biology*. University of California Press, Berkeley, 179-186, 1974.
- [Campbell, 1974b] D. T. Campbell. Evolutionary epistemology. In P. A. Schilpp (ed.), *The philosophy of Karl Popper*. Open Court, La Salle Ill., 1974.
- [Campbell, 1977] D. T. Campbell. Comment on "The natural selection model of conceptual evolution". *Philosophy of Science*, 44, 502-507, 1977.
- [Campbell, 1986] D. T. Campbell. Science's social system of validity-enhancing collective belief change and the problems of the social sciences. In D. W. Fiske, R. A. Shwader (eds.), *Pluralisms and subjectivities*. University of Chicago Press, Chicago, 1986.
- [Campbell and Paller, 1989] D. T. Campbell, B.T. Paller. Extending Evolutionary Epistemology to 'Justifying' Scientific Beliefs. In [Hahlweg and Hooker, 1989b], pp. 231-257, 1989.
- [Campbell, 1997] D. T. Campbell. From evolutionary epistemology via selection theory to a sociology of scientific validity. *Evolution and Cognition*, 3, 5-38, 1977.
- [Cariani, 1992] P. Cariani. Some epistemological implications of devices which construct their own sensors and effectors. In F. Varela and P. Bourguine (eds.), *Towards a practice of autonomous systems*. MIT Press, Cambridge Mass., 1992.
- [Cariani, 1993] P. Cariani. To evolve an ear. *Systems research*, 10(3), 19-33, 1993.
- [Cash *et al.*, 2006] D. W. Cash, W. N. Adger, F. Berkes, P. Garden, L. Lebel, P. Olsson, L. Pritchard, O. Young. Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World. *Ecology and Society*, 11(2), 2006. <http://www.ecologyandsociety.org/>
- [Cenys *et al.*, 2003] A. Cenys, A. Tamasevicius, A. Baziliauskas, R. Krivickas, E. Lindberg. Hyperchaos in coupled Colpitts oscillators. *Chaos, Solitons & Fractals*, 17(23), 3493-353, 2003.
- [Cherniak, 1986] C. Cherniak. *Minimal rationality*. MIT Press, Cambridge, Mass., 1986.
- [Christensen, 1999] W. D. Christensen. *An interactivist-constructivist approach to adaptive intelligence and agency*, PhD thesis, University of Newcastle, Australia, 1999.

- [Christensen and Hooker, 1998] W. D. Christensen and C. A. Hooker. From cell to scientist: Toward an organisational theory of life and mind. In J. Bigelow (ed.), *Our Cultural Heritage*. Australian Academy of Humanities, University House, Canberra, 275-326, 1988.
- [Christensen and Hooker, 1999] W. D. Christensen and C. A. Hooker. The organization of knowledge: beyond Campbell's evolutionary epistemology. *Philosophy of Science*, 66, Proceedings, PSA 1998, S237-S249, 1999.
- [Christensen and Hooker, 2000a] W. D. Christensen and C. A. Hooker. Organised interactive construction: The nature of autonomy and the emergence of intelligence. In A. Etxeberria, A. Moreno, J. Umerez (eds.), *The Contribution of Artificial Life and the Sciences of Complexity to the Understanding of Autonomous Systems, Communication and Cognition*, special edn, 17(3-4), 133-158, 2000.
- [Christensen and Hooker, 2000b] W. D. Christensen and C. A. Hooker. An Interactivist-Constructivist Approach to Intelligence: Self-directed Anticipative Learning. *Philosophical Psychology*, 13, 5-45, 2000.
- [Christensen and Hooker, 2002] W. D. Christensen and C. A. Hooker. Self-directed agents. In J. MacIntosh (ed.), *Naturalism, Evolution and Intentionality*, Ottawa, *Canadian Journal of Philosophy*, Special Supplementary Volume 27, 19-52, 2002.
- [Christensen and Hooker, 2004] W. D. Christensen and C. A. Hooker. Representation and the meaning of life. In H. Clapin, P. Staines, P. Slezak (eds.), *Representation in mind: new approaches to mental representation*. Sydney, Elsevier, 41-69, 2004.
- [Churchland, 1989] P. M. Churchland. *A Neurocomputational Perspective: The Nature of Mind and the Structure of Science*. Bradford/MIT Press, Cambridge, Mass., 1989.
- [Churchland, 1995] P. M. Churchland. *The Engine of Reason, the Seat of the Soul*, MIT Press, Cambridge Mass., 1995.
- [Churchland, 1986] P. S. Churchland. *Neuro-philosophy: toward a unified understanding of the mind-brain*. MIT Press, Cambridge Mass., 1986.
- [Clark, 1997] A. Clark. *Being There: Putting Brain, Body, and World Together Again*. Bradford/MIT Press, Boston, 1997.
- [Collier and Hooker, 1999] J. D. Collier and C. A. Hooker. Complex Organised Dynamical Systems. *Open Systems and Information Dynamics*, 6, 241-302, 1999.
- [Coltheart, 2006a] M. Coltheart. What has functional neuroimaging told us about the mind (so far)? *Cortex*, 42, 323-331, 2006.
- [Coltheart, 2006b] M. Coltheart. Perhaps functional neuroimaging has not told us anything about the mind (so far). *Cortex*, 42, 422-427, 2006.
- [Cragg, 1989] B. Cragg. Evolution of the steam engine. In [Hahlweg and Hooker, 1989b], pp. 313-356, 1989.
- [Craver, 2002] C. Craver. Interlevel experiments and multilevel mechanisms in the neuroscience of memory. *Philosophy of Science Supplement*, 69, S83-S97.
- [Craver, 2007] C. Craver. *Explaining the brain: mechanisms and the mosaic unity of neuroscience*. Oxford University Press, Oxford, 2007.
- [Craver and Bechtel, 2007] C. F. Craver and W. Bechtel. Topdown causation without topdown causes. *Biology and Philosophy*, 22, 547-563, 2007.
- [Crutchfield, 1994] J. Crutchfield. The calculi of emergence: computation, dynamics and induction. *Physica D*, 75, 11-54, 1994.
- [Cumming and Collier, 2009] G. Cumming and J. Collier. Change and identity in complex systems. In B. Brown, K. de Laplante, K. Peacock (eds.), *Philosophy of Ecology*. Elsevier, Amsterdam, 2009.
- [Cunningham, 1972] M. Cunningham. *Intelligence: Its Origin and Development*. Academic Press, New York, 1972.
- [Depew, Weber, 1999] D. Depew, B. Weber. *Darwinism Evolving*. MIT, Cambridge Mass., 1999.
- [Dieckmann et al., 2000] U. Dieckmann, R. Law, J. Metz (eds.). *The Geometry of Ecological Interactions: Simplifying Spatial Complexity*. Cambridge University Press, Cambridge, 2000.
- [Dreyfus, 1996] H. Dreyfus. The current relevance of Merleau-Ponty's phenomenology of embodiment. H. Haber, G. Weiss (eds.), *Perspectives on embodiment*. Routledge, London, 1996.
- [Dreyfus and Dreyfus, 1986] H. L. Dreyfus, S. E. Dreyfus. *Mind over machine*. Blackwell, Oxford, 1986.
- [Dyke, 1988] C. Dyke. *The evolutionary dynamics of complex systems*. Oxford University Press, Oxford, 1988.

- [Earman *et al.*, 2002] J. Earman, C. Glymour, S. Mitchell. *Ceteris paribus laws*. Kluwer, Boston, 2002.
- [Eigen and Schuster, 1979] M. Eigen and P. Schuster. *The Hypercycle: A principle of natural selforganization*. Springer, Berlin, 1979.
- [Eigen and Winkler, 1993] M. Eigen and R. Winkler. *The Laws of the Game: How The Principles of Nature Govern Chance*. Princeton University Press, Princeton, 1993.
- [Eldredge, 1985] N. Eldredge. *Unfinished Synthesis: Biological Hierarchies and Modern Evolutionary Thought*. Oxford University Press, New York, 1985.
- [Elias-Smith, 2000] C. Eliasmith. Is the brain analog or digital? The solution and its consequences for cognitive science. *Cognitive Science Quarterly*, 1(2),147170, 2000.
- [Elias-Smith, 2009a] Dynamics, control and cognition. In P. Robbins, M. Aydede (eds.), *Cambridge Handbook of Situated Cognition*. Cambridge University Press, Cambridge, 2009.
- [Elias-Smith, 2009b] Computational neuroscience. In P. Thagard (ed.), *Philosophy of Psychology and Cognitive Science*. Handbook of the Philosophy of Science, vol. 4, Elsevier, Amsterdam, 2009.
- [Emmeche *et al.*, 2000] C. Emmeche, S. Koppe, F. Stjernfelt. Levels, emergence, and three versions of downward causation. In [Andersen, *et al.*, 2000], pp. 13-34, 2000.
- [Epstein, 2007] J. M. Epstein. *Generative social science: studies in agentbased computational modeling*, Princeton University Press, Princeton, 2007.
- [Espejo and Harnden, 1989] R. Espejo and R. Harnden (eds.). *The Viable System Model*. John Wiley, New York, 1989.
- [Etzeberria, 1998] A. Etzeberria. Embodiment of natural and artificial agents. In G. van der Vijver, S. N. Salthe and M. Delpo (eds.), *Evolutionary Systems*. Reidel, Dordrecht, 1998.
- [Etzeberria and Moreno, 2001] A. Etzeberria and A. Moreno. From complexity to simplicity: nature and symbols. *BioSystems*, 60, Special issue on the Physics and Evolution of Symbols and Codes: Reflections on the Work of Howard Pattee, 149-157, 2001.
- [Farrell and Hooker, 2007a] R. Farrell and C. A. Hooker. Applying self-directed anticipative learning to science: agency and the interactive exploration of possibility space in ape language research. *Perspectives on Science*, 15(1), 86-123, 2007.
- [Farrell and Hooker, 2007b] R. Farrell and C. A. Hooker. Applying self-directed anticipative learning to science: learning how to learn across revolutions. *Perspectives on Science*, 15(2), 220-253, 2007.
- [Farrell and Hooker, 2009] R. Farrell and C. A. Hooker. Applying self-directed anticipative learning to science: identifying error and severe testing through interactive exploration of possibility. *Foundations of Science*, 2009.
- [Ferber, 1999] J. Ferber. *Multi-agent Systems: An Introduction to Distributed Artificial Intelligence*, Addison -Wesley, New York, 1999.
- [Fogel *et al.*, 2008] A. Fogel, B. J. King, S. G. Shankar. *Human development in the twenty first century: visionary ideas from systems scientists*. Cambridge University Press: Cambridge, 2008.
- [Fox Keller, 2005] E. Fox Keller. Revisiting 'scale-free' networks. *BioEssays*, 27, 1060-1068, 2005.
- [Fox Keller, 2007] E. Fox Keller. The disappearance of function from 'self-organizing systems'. In [Boogerd, *et al.*, 2007], pp. 303-317, 2007.
- [Fu and Panke, 2009] P. Fu and S. Panke. eds. *Systems Biology and Synthetic Biology*, Wiley, Hoboken N.J., 2009.
- [Gánti, 2003] T. Gánti. *The principles of life*. Oxford University Press, New York, 2003.
- [Gao, 2005] Y. Gao. *Ecologies of Scientific Practice: An Analysis of the Organization and Dynamics of Science*. PhD thesis, University of Newcastle, Newcastle, Australia, 2005.
- [Galison, 1987] P. Galison. *How experiments end*. Chicago: University of Chicago Press.
- [Gell-Mann, 1994] M. Gell-Mann. *The Quark and the Jaguar: Adventures in the Simple and the Complex*. Henry Holt, New York, 1994.
- [Glass, 1988] L. Glass, M. Mackey. *From Clocks to Chaos*. Princeton University Press, Princeton, 1988.
- [Gleick, 1988] J. Gleick. *Chaos: making a new science*. Penguin, New York, 1988.
- [Goldbeter, 1996] A. Goldbeter. *Biochemical Oscillations and Cellular Rhythms: the Molecular Bases of Periodic and Chaotic Behaviour*. Cambridge University Press: Cambridge, 1996.



- [Goldspink, 2002] C. Goldspink. Methodological implications of complex systems approaches to sociality: simulation as a foundation for knowledge. *Journal of Artificial Societies and Social Simulation*, 5(1), 2002. Available at <http://jasss.soc.surrey.ac.uk/5/1/3.html>.
- [Goldstein, 2002] J. Goldstein. The singular nature of emergent levels: suggestions for a theory of emergence. *Non-linear dynamics, psychology, and life sciences*, 6(4), 293-309, 2002.
- [Goodwin, 1994] B. Goodwin. *How the leopard changed its spots*. Weidenfeld & Nicolsen, London, 1994.
- [Goodwin and Saunders, 1989] B. Goodwin and P. Saunders. *Theoretical Biology: Epigenetic and Evolutionary Order from Complex Systems*. Edinburgh University Press, Edinburgh, 1989.
- [Gray, 1992] R. Gray. Death of the gene: developmental systems strike back. In P. Griffiths (ed.), *Trees of Life: Essays in Philosophy of Biology*. Kluwer, Dordrecht, 1992.
- [Gray and Scott, 1994] P. Gray and S. K. Scott. *Chemical Oscillations and Instabilities: Non-linear Chemical Kinetics*. Clarendon Press: Oxford England, 1994.
- [Griffiths, 1992] P. E. Griffiths (ed.). *Trees of Life: Essays in Philosophy of Biology*. Kluwer, Dordrecht, 1992.
- [Griffiths and Stotz, 2007] P. E. Griffiths and K. Stotz. Gene. In M. Ruse, D. Hull (eds.), *Cambridge Companion to Philosophy of Biology*. Cambridge University Press, Cambridge, 85-102, 2007.
- [Groß and Dorigo, 2007] R. Groß and M. Dorigo. Fifty years of selfassembly experimentation. In W.M. Shen, H. Lipson, K. Stoy, M. Yim (eds.), *Proceedings of the Workshop on Self-Reconfigurable Robots/Systems and Applications*, USC Information Science Institute, 2007
- [Groß and Dorigo, 2008] R. Groß and M. Dorigo. Selfassembly at the macroscopic scale. *Proceedings of IEEE*, 96(9), 14901508, 2008.
- [Guckenheimer and Holmes, 1983] J. Guckenheimer and P. Holmes. *Non-linear oscillations, dynamical systems and bifurcations of vector fields*. Springer, New York, 1983.
- [Gunderson et al., 1997] L. Gunderson, C. Holling, L. Pritchard, G. Peterson. *Resilience in Ecosystems, Institutions and Societies*. Beijer Discussion Paper Series, No. 95. Beijer International Institute of Ecological Economics, Stockholm, 1997.
- [Gunderson and Holling, 2002] L. Gunderson and C. Holling (eds.). *Panarchy: Understanding Transformations in Human and Natural Systems*. Washington, Island Press, 2002.
- [Hahlweg, 1983] K. Hahlweg. *The evolution of science: a systems approach*. Ph.D. thesis, University of Western Ontario, Canada, 1983.
- [Hahlweg, 1991] K. Hahlweg. On the notion of evolutionary progress. *Philosophy of science* 58, 436-51, 1991.
- [Hahlweg and Hooker, 1989a] K. Hahlweg and C. A. Hooker. Evolutionary epistemology and philosophy of science. In [Hahlweg and Hooker, 1989b], 21-150.
- [Hahlweg and Hooker, 1989b] K. Hahlweg and C. A. Hooker (eds.). *Issues in Evolutionary Epistemology*. State University of New York Press, Albany N.Y., 1989.
- [Haila and Levins, 1992] Y. Haila and R. Levins. *Humanity and Nature: Ecology, Science and Society*. Pluto Press, London, 1992.
- [Haken, 1983] H. Haken. *Synergetics, an Introduction: Nonequilibrium Phase Transitions and SelfOrganization in Physics, Chemistry, and Biology*, 3rd rev. enl. edn. SpringerVerlag, New York, 1983.
- [Haken, 1993] H. Haken. *Advanced Synergetics: Instability Hierarchies of SelfOrganizing Systems and Devices*. SpringerVerlag, New York, 1993.
- [Hastie et al., 2008] T. Hastie, R. Tibshirani, J. H. Friedman. *The elements of statistical learning: data mining, inference, and prediction*, 2<sup>nd</sup> edn. Springer, New York, 2008.
- [Heath, 2000] R. Heath. *Nonlinear Dynamics: Techniques and Applications in Psychology*. Erlbaum, Mahwah, N.J., 2000.
- [Heylighen, 1991] F. Heylighen. Modelling emergence. *World futures (Journal of general evolution)*, 31 (Special Issue on Emergence, edited by G. Kampis), 89104, 1991.
- [Herfel and Hooker, 1996] W. E. Herfel and C. A. Hooker. Cognitive dynamics and the development of science. In D. Ginev and R. S. Cohen (eds.), *Issues and images in the philosophy of science*. Kluwer, Boston, 127-172, 1996.
- [Herfel and Hooker, 1999] W.E. Herfel and C. A. Hooker. From formal machine to social colony: toward a complex dynamical philosophy of science. In M. L. Dalla Chiara, R. Giuntini, F. Laudisa (eds.), *Language, Quantum, Music: Select Proceedings of the 10th International Congress of Logic, Methodology and Philosophy of Science*. Boston, Kluwer, 7-18, 1999.

- [Heiby *et al.*, 2003] E. M. Heiby, I. Pagano, D. Blaine, K. Nelson, R. A. Heath. Modeling unipolar depression as a chaotic process. *Psychological Assessment*, 15, 426-434, 2003.
- [HoyningenHuene, 1993] P. HoyningenHuene. *Reconstructing Scientific Revolutions: Thomas S. Kuhn's Philosophy of Science*. University of Chicago Press, Chicago, 1993.
- [Hodges, 1997] B. Hodges. *Retooling Popper: conventional decision and the rationality of improvement*. PhD thesis, University of Newcastle, Newcastle, Australia, 1997.
- [Hogeweg, 2002a] P. Hogeweg. Computing an organism: on the interface between informatic and dynamic processes. *Biosystems*, 64, 97-109, 2002.
- [Hogeweg, 2002b] P. Hogeweg. Multilevel processes in evolution and development: computational models and biological insights. In M. Lässig, A. Valleriani (eds.), *Biological Evolution and Statistical Physics*. Springer lecture notes in physics 585, Springer Verlag, Berlin, 217-239, 2002.
- [Hogeweg and Takeuchi, 2003] P. Hogeweg and N. Takeuchi. Multilevel selection in models of prebiotic evolution: compartments and spatial self-organization. *Origins of Life and Evolution of the Biosphere*, 33, 375-403, 2003.
- [Holland, 1995] J. Holland. *Hidden Order: How Adaptation Builds Complexity*. Addison Wesley, Redwood City, Cal.; Perseus Books, Cambridge MA, 1995.
- [Holland 1998, ] J. H. Holland. *Emergence: from chaos to order*. Addison Wesley, Redwood City, Cal.; Basic Books, New York, 1998.
- [Holling, 1992] C. Holling. Cross-scale morphology, geometry and dynamics of ecosystems. *Ecological monographs*, 62(4), 447-502, 1992.
- [Holmes, 2005] P. Holmes. Ninety plus thirty years of nonlinear dynamics: less is more and more is different. *International Journal of Bifurcation and Chaos*, 15(9), 2703-2716.
- [Hommes, 2001] C. H. Hommes. Financial markets as nonlinear adaptive evolutionary systems. *Quantitative Finance*, 1, 14967, 2001.
- [Hooker, 1978] C. A. Hooker. An Evolutionary Naturalist Realist Doctrine of Perception and Secondary Qualities. In C. W. Savage (ed.), *Minnesota Studies in the Philosophy of Science* Vol. IX. University of Minnesota Press, Minneapolis, 405-440, 1978.
- [Hooker, 1981a] C. A. Hooker. Formalist rationality: the limitations of Popper's theory of reason. *Metaphilosophy* 12, 247-266, 1981.
- [Hooker, 1981b] C. A. Hooker. Towards a general theory of reduction. *Dialogue*, XX, Part I, Historical framework, 38-59, Part II, Identity and reduction, 201-36, Part III, Cross-categorical reduction, 496-529, 1981.
- [Hooker, 1987] C. A. Hooker. *A Realistic Theory of Science*. State University of New York Press, Albany NY, 1987.
- [Hooker, 1989] C. A. Hooker. From logical formalism to control system. in A. Fine, J. Leplin (eds.), *PSA 1988*, East Lansing, Philosophy of Science Association, 211-221, 1989.
- [Hooker, 1994a] C. A. Hooker. Idealisation, naturalism, and rationality: some lessons from minimal rationality. *Synthese*, 99, 181-231, 1994.
- [Hooker, 1994b] C. A. Hooker. From phenomena to metaphysics. In D. Prawitz, D. Westerstahl (eds.), *Logic and Philosophy of Science in Uppsala*. Dordrecht, Kluwer, 159-184, 1994.
- [Hooker, 1994c] C. A. Hooker. Regulatory constructivism: on the relation between evolutionary epistemology and Piaget's genetic epistemology. *Biology and Philosophy*, 9, 197-244, 1994.
- [Hooker, 1995a] C. A. Hooker. Toward a naturalised cognitive science. In R. Kitchener, W. O'Donohue (eds.), *Psychology and Philosophy*. Allyn and Bacon, London, 184-206, 1995.
- [Hooker, 1995b] C. A. Hooker. *Reason, regulation and realism*. State University of New York Press, Albany, 1995.
- [Hooker, 2000] C. A. Hooker. Unity of science. In W. H. Newton-Smith (ed.), 2000, *A Companion to the Philosophy of Science*. Blackwell, Oxford, 540-549, 2000.
- [Hooker, 2002] C. A. Hooker. An integrating scaffold: toward an autonomy-theoretic modelling of cultural change. In M. Wheeler, J. Ziman (eds.), *The Evolution of Cultural Entities*. British Academy of Science & Oxford University Press, Oxford, 2002.
- [Hooker, 2004] C. A. Hooker. Asymptotics, reduction and emergence. *British Journal for the Philosophy of Science*, 55, 435-479, 2004.
- [Hooker, 2009a] C. A. Hooker. On fundamental implications of systems and synthetic biology. In [Fu and Panke, 2009], 2009.
- [Hooker, 2009b] C. A. Hooker. Interaction and bio-cognitive order. *Synthese*, 166(3), 513-546, 2009.

- [Hooker-b, this volume] Introduction to philosophy of complex systems. Part B: Scientific paradigm + philosophy of science for complex systems: a first presentation c. 2009. In this volume.
- [Hooker-c, this volume] Conceptualising reduction, emergence and self-organisation in complex dynamical systems. In this volume.
- [Howard, 1971] N. Howard. *Paradoxes of rationality: theory of metagames and political behaviour*. MIT Press, Cambridge Mass., 1971.
- [Humphries, 1994] P. Humphries. Numerical experimentation. In P. Humphries (ed.), *Patrick Suppes, scientific philosopher*. vol. 2. Kluwer, Dordrecht, 103-118, 1994.
- [Humphries, 2004] P. Humphries. *Extending ourselves: computational science, empiricism and scientific method*. Oxford University Press, Oxford, 2004.
- [Icke, 1995] Icke. *The force of symmetry*. Cambridge University Press, Cambridge, 1995.
- [Jablonka and Lamb, 1995] E. Jablonka, M. Lamb. *Epigenetic Inheritance and Evolution: The Lamarckian Dimension*. Oxford University Press, Oxford, 1995.
- [Jablonka and Lamb, 2005] E. Jablonka and M. Lamb. *Evolution in Four Dimensions: Genetic, Epigenetic, Behavioral, and Symbolic Variation in the History of Life*. MIT Press, Cambridge, Mass., 2005.
- [Juarrero, 2002] A. Juarrero. *Dynamics in action: intentional behavior as a complex system*. MIT Press, Cambridge, Mass., 2002.
- [Kaplan and Glass, 1995] D. Kaplan and L. Glass. *Understanding Nonlinear Dynamics*. Springer-Verlag, New York, 1995.
- [Kauffman, 1995] S. Kauffman. *At Home in the Universe*. Oxford University Press, Oxford, 1995.
- [Kauffman, 2000] S. Kauffman. *Investigations*. Oxford University Press, New York, 2000.
- [Keilis-Borok and Soloviev, 2003] V. I. Keilis-Borok and A. A. Soloviev, eds. *Nonlinear dynamics of the lithosphere and earthquake prediction*. New York, Springer, 2003.
- [King, 2003] R. B. King. Chirality and Handedness: The Ruch "ShoePotato" Dichotomy in the RightLeft Classification Problem. *Annals of the New York Academy of Science*, 988, 158170, 2003.
- [Kohlmorgan et al., 1999] U. Kohlmorgen, H. Schmeck and K. Haase. Experiences with fine grained parallel genetic algorithms. *Annals of Operations Research*, 90, 203-219, 1999.
- [Kuhn, 1962] T. S. Kuhn. *The Structure of Scientific Revolutions*, 1st. ed.n. University of Chicago Press, Chicago, 1962. 2<sup>nd</sup> edn, with postscript, 1970.
- [Kubic, 2003] A. Kubic. Toward a formalization of emergence. *Artificial Life*, 9(1), 41-65, 2003.
- [Lakatos and Musgrave, 1970] I. Lakatos, A. Musgrave (eds.). *Criticism and the Growth of Knowledge*. Cambridge University Press, London, 1970.
- [Lalonde et al., 2000] K. N. Laland, J. Odling-Smee, M. W. Feldman. Niche Construction, Biological Evolution and Cultural Change. *Behavioral and Brain Sciences*, 23 (1), 131-146, 2000.
- [Landau, 1937] L. D. Landau. Broken symmetry and phase transitions. *Transactions Physics Zeitschrift Sowjetunion*, 11, 26, 542, 1937.
- [Latour, 1987] B. Latour. *Science in action*. Harvard University Press, Cambridge Mass., 1987.
- [Latour and Woolgar, 1979] B. Latour and S. Woolgar. *Laboratory life: the social construction of scientific facts*. Sage, Beverley Hills, 1979.
- [Layzer, 1990] D. Layzer. *Cosmogenesis: the growth of order in the universe*. Oxford University Press, New York, 1990.
- [Leonard, 1999] A. Leonard. A Viable System Model: Consideration of Knowledge Management. *Journal of Knowledge Management Practice*, August 1999. Accessed at <http://www.tlainc.com/artic112.htm>, June 2009.
- [Lewis, 2005] M. D. Lewis. Bridging emotion theory and neurobiology through dynamic systems modeling. *Behavioural and Brain Sciences*, 28, 168-245, 2005.
- [Lewis and Todd, 2007] M. D. Lewis and R. M. Todd. The selfregulating brain: cortical-subcortical feedback and the development of intelligent action. *Cognitive Development*, 22, 406430, 2007.
- [Lewis and Cook, 2007] M. D. Lewis, M. L. Cook. Changing habits of emotion regulation at transition points in infancy: A dynamic systems analysis. *Journal of Developmental Processes*, 3, 6789, 2007.

- [Lindberg, 2004] E. Lindberg. On the mechanisms behind chaos. *Proceedings of the 12th Workshop on Nonlinear Dynamics of Electronic Systems*, NDES 2004. Evora, Portugal, 227230, 2004.
- [Lorenz, 1997] H.-W. Lorenz. *Nonlinear Dynamical Economics and Chaotic Motion*. (1<sup>st</sup> edn 1989, 2<sup>nd</sup> rev. & enl. edn, 1993.) Springer, Berlin, 1997.
- [Mainzer, 2005] K. Mainzer. *Symmetry and Complexity: the Spirit and Beauty of Non-linear Science*, World Scientific, Singapore, 2005.
- [Marr, 1982] D. Marr. *Vision*. MIT Press, Cambridge, Mass., 1982.
- [Maturana, 1981] H. R. Maturana. Autopoiesis. In M. Zeleny (ed.), *Autopoiesis: A theory of the living organization*. Westview Press, Boulder, 1981.
- [Maturana and Varela, 1980] H. Maturana and F. Varela. *Autopoiesis and cognition*. Reidel, Dordrecht, 1980.
- [May, 1976] R. May, ed. *Theoretical Ecology: Principles and Applications*. Saunders, Philadelphia, 1976.
- [Mayo, 1996] D. Mayo. *Error and the Growth of Experimental Knowledge*. University of Chicago Press, Chicago, 1996.
- [Maynard-Smith, 1986] J. Maynard-Smith. *The problems of biology*. Oxford University Press, New York, 1986.
- [Maynard-Smith and Szathmary, 1995] J. Maynard-Smith and E. Szathmary. *The major transitions in evolution*. Freeman, New York, 1995.
- [Mayr, 2004] E. Mayr *What Makes Biology Unique?* Cambridge University Press, Cambridge, 2004.
- [McCulloch and Pitts, 1943] W. S. McCulloch and W. Pitts. A logical calculus of the ideas immanent in nervous activity. *Bulletin of Mathematical Biophysics*, 5, 115-133, 1943. But cf. <http://www.dlsi.ua.es/~mlf/nnafmc/pbook/node10.html>.
- [McKelvey, 1999] B. McKelvey. Complexity theory in organization science: seizing the promise or becoming a fad?. *Emergence*, 1(1), 5-32, 1999.
- [McLaughlin, 1992] B. McLaughlin. The rise and fall of British emergentism. In A. Beckerman, H. Flor, J. Kim (eds.), *Emergence or reduction?: essays on the prospect of nonreductive physicalism*. de Gruyter, Berlin, 1992. Reprinted in [Bedau and Humphries, 2008, pp. 19-60].
- [Merleau-Ponty, 1962] M. Merleau-Ponty. *Phenomenology of perception* (transl. C. Smith). Routledge & Kegan-Paul, London, 1962.
- [Miklos, 1993] G. Miklos. Molecules and cognition: the latterday lessons of levels, language and lac. *Journal of Neurobiology*, 24, 842-890, 1993.
- [Miller, 1956] G. A. Miller. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81-97, 1956.
- [Moreno, 2007] A. Moreno. A systemic approach to the origin of biological organization. In [Boogerd, et al., 2007, pp. 243-268].
- [Moreno and Ruiz-Mirazo, 1999, ] A. Moreno and K. Ruiz-Mirazo. Metabolism and the problem of its universalization, *Biosystems*, 49, 45-61, 1999.
- [Moreno and Lasa, 2003] A. Moreno and A. Lasa. From basic adaptivity to early mind: the origin and evolution of cognitive capacities, *Evolution and Cognition*, 9(1), 12-30, 2003.
- [Morowitz, 1978] H. J. Morowitz. *Foundations of bioenergetics*. Academic Press, New York, 1978.
- [Morowitz, 2002] H. J. Morowitz. *The Emergence of Everything*. Oxford University Press, Oxford, 2002.
- [Morowitz and Singer, 1995] H. J. Morowitz, J. L. Singer (eds.). *The Mind, The Brain, and Complex Adaptive Systems*. Addison-Wesley, Reading Mass., 1995.
- [Mossio et al., 2009] M. Mossio, G. Longo, J. Stewart. A computable expression of closure to efficient causation, *Journal of Theoretical Biology*, in press, 2009. (<http://dx.doi.org/10.1016/j.jtbi.2008.12.012>)
- [Nagel, 1961] E. Nagel. *The Structure of Science*. Routledge & Kegan Paul, London, 1961.
- [Nelson and Winter, 1982] R. R. Nelson and S. G. Winter. *An Evolutionary Theory of Economic Change*. Harvard University Press, Harvard, 1982.
- [Nicolis, 1986] J. S. Nicolis. *Dynamics of hierarchical systems: an evolutionary approach*. Springer, Berlin, 1986.
- [O'Connor and Wong, 2002] T. O'Connor and H. Y. Wong. Emergence. Stanford Encyclopedia of Philosophy, <http://plato.stanford.edu/entries/properties-emergent/>, 2002.
- [Odum, 1971] H. Odum. *Environment, Power and Society*. Wiley, New York, 1971.

- [Oldroyd, 1989] D. Oldroyd. *The arch of knowledge*. University of NSW Press, Kensington N.S.W., 1989.
- [Oreskes, 2000a] N. Oreskes. Why believe a computer? Models, measures, and meaning in the natural world. In J. S. Schneiderman (ed.) *The Earth Around Us: Maintaining a Livable Planet*. San Francisco, W.H. Freeman and Co., 7082, 2000a.
- [Oreskes, 2000b] N. Oreskes. Why predict? Historical perspectives on prediction in the earth sciences. In D. Sarewitz, R. Pielke, Jr., R. Byerly, Jr. (eds.) *Prediction: Decisionmaking and the Future of Nature*. Washington, D.C., Island Press, 2340, 2000b.
- [Oreskes, 2003] N. Oreskes. The role of quantitative models in science. In C. D. Canham, J. J. Cole, W. K. Lauenroth (eds.) *Models in Ecosystem Science*. Princeton, Princeton University Press, 1331, 2003.
- [Oreskes, 2007] N. Oreskes. From scaling to simulation: Changing meanings and ambitions of models in the Earth sciences. In A. N. H. Creager, E. Lunbeck, M. N. Wise (eds.) *Science without Laws: Model Systems, Cases, and Exemplary Narratives*. Duke University Press, 2007.
- [Oreskes and Fleming, 2000] N. Oreskes, J. R. Fleming, (eds.). Perspectives on Geophysics. Special Issue of Studies in the History and Philosophy of Modern Physics, 31B, September 2000.
- [Oyama et al., 2001] S. Oyama, P. Griffiths, R. Gray (eds.), *Cycles of Contingency: Developmental Systems and Evolution*, MIT Press, Cambridge Mass., 2001.
- [Pahl-Wostl, 1995] C. Pahl-Wostl. *The Dynamic Nature of Ecosystem: Chaos and Order Entwined*. Wiley, New York, 1995.
- [Pask, 1960] G. Pask. The natural history of networks. In M. C. Yovits, S. Cameron (eds.), *Self-organizing systems*. Pergamon, New York, 1960.
- [Pask, 1981] G. Pask. Organisational closure of potentially conscious systems. In M. Zeleny (ed.), *Autopoiesis: A theory of living organisation*. North Holland, New York, 1981.
- [Pattee, 1973] H. H. Pattee (ed.). *Hierarchy theory: the challenge of complex systems*. New York: Geo. Braziller, 1973.
- [Pattee, 1993] H. H. Pattee. The limitations of formal models of measurement, control, and cognition. *Applied Math. and Computation*, 56, 111-130, 1993.
- [Pattee, 1995] H. H. Pattee. Evolving self-reference: matter, symbols, and semantic closure. *Communication and Cognition — Artificial Intelligence*, 12 (1-2), 9-28, 1995.
- [Pattee, 1996] H. H. Pattee. The problem of observables in models of biological organizations. In E. L. Khalil, K. E. Boulding (eds.), *Evolution, Order, and Complexity*. Routledge, London, 1996.
- [Pattee, 2000] H. H. Pattee. Causation, control and the evolution of complexity. In [Andersen et al., 2000, pp. 322-348].
- [Pattee, 2007] H. H. Pattee. Laws, constraints and the modelling relation — history and interpretations. *Chemistry & Biodiversity*, 4, 2272-2278, 2007.
- [Penfold et al., 1993] H. B. Penfold, P. S. Champness, U. Kohlmorgen. Breeding neural nets using a genetic algorithm on a massively parallel computer. Research Report, Electrical Engineering, Universities of Karlsruhe and Newcastle, 1993.
- [Pfeiffer and Bongard, 2007] R. Pfeiffer and J. C. Bongard. *How the body shapes the way we think: a new view of intelligence*. MIT Press, Cambridge Mass., 2007.
- [Piaget, 1971a] J. Piaget. *Insights and illusions of philosophy* (trans. W. Mays). Meridian, New York, 1971.
- [Piaget, 1971b] J. Piaget. *Biology and knowledge: an essay on the relations between organic regulations and cognitive processes* (trans. B. Walsh). University of Chicago Press, Chicago, 1971.
- [Piaget and Garcia, 1989] J. Piaget and R. Garcia. *Psychogenesis and the history of science* (trans. H. Feider). Columbia University Press, New York, 1989.
- [Pines, 1985] D. Pines, ed. *Emerging Syntheses in Science, Proceedings of the founding workshops of the Santa Fe Institute*, Addison Wesley, Redwood California, 1985.
- [Polanyi, 1968] M. Polanyi. Life's irreducible structure. *Science*, 160, 1308-1312, 1968.
- [Poon and Andelman, 2006] W. C. K. Poon and D. Andelman. *Soft condensed matter physics in molecular and cell biology*. Taylor & Francis, London, 2006.
- [Popper, 1972] K. Popper. *Conjectures and Refutations*. Routledge and Kegan Paul, London, 1972.
- [Popper, 1979] K. Popper. *Objective knowledge: an evolutionary approach* (rev. ed.). Oxford University Press, Oxford, 1979.

- [Popper, 1984] K. Popper. Evolutionary epistemology. In J. W. Pollard (ed.), *Evolutionary theory: paths into the future*. Wiley, Chichester, 1984.
- [Popper, 1987] K. Popper. Natural selection and the emergence of mind. In G. Radnitzky, W. W. Bartley III (eds.), *Evolutionary epistemology, theory of rationality and sociology of knowledge*. Open Court, La Salle Ill., 1987.
- [Port and van Gelder, 1995] R. Port, T. J. van Gelder. *Mind as Motion: Dynamics, Behavior, and Cognition*. MIT Press, Cambridge Mass., 1995.
- [PourEl and Richards, 1989] M. PourEl and J. I. Richards. *Computability and Analysis in Physics*, Perspectives in Mathematical Logic. SpringerVerlag, Berlin, 1989.
- [Prigogine, 1967] I. Prigogine. *Thermodynamics of Irreversible Processes*, 3<sup>rd</sup> edn. Wiley/Interscience, New York, 1967.
- [Prigogine, 1980] I. Prigogine. *From Being to Becoming*, W. H. Freeman, San Francisco, 1980.
- [Prigogine, 2003] I. Prigogine. Chemical Kinetics and Dynamics. *Annals of the New York Academy of Science*, 988, 128132, 2003.
- [Prigogine and Stengers, 1984] I. Prigogine and I. Stengers. *Order out of Chaos*, Shambhala, Boulder, Colorado, 1984.
- [Prokopenko, 2008] M. Prokopenko, ed. *Advances in Applied Selforganizing Systems*. Advanced Information and Knowledge Processing Series, Springer, Berlin, 2008.
- [Putnam, 1975] *Mind, Language and Reality*. Philosophical Papers, vol. 2. Cambridge University Press, Cambridge, 1975.
- [Raff and Kaufman, 1983] R. Raff, T. Kaufman. *Embryos, Genes, and Evolution*. Macmillan, New York, 1983.
- [Raff, 1996] R. A. Raff. *The shape of life: genes, development and the evolution of animal form*. University of Chicago Press, Chicago, 1996.
- [Rapoport, 1966] A. Rapoport. *Two person game theory*, University of Michigan Press, Ann Arbor, 1966.
- [Rapoport, 1970] A. Rapoport. *Fights, games and debates*. University of Michigan Press, Ann Arbor, 1970.
- [Rashevsky, 1964] N. Rashevsky. *Some Medical Aspects of Mathematical Biology*. Thomas, Springfield, IL., 1964.
- [Ravasz *et al.*, 2002] E. Ravasz, A.L. Somera, D.A. Mongru, Z.N. Oltavai, and A.L. Barabási. Hierarchical Organization of Modularity in Metabolic Networks. *Science*, 297, 15511555, 2002.
- [Rescher, 1977] N. Rescher. *Methodological pragmatism*. Blackwell, London, 1977.
- [Roos, 1927] C. F. Roos. Dynamical Economics. *Proceedings of the National Academy of Science*, 13, 145150, 1927.
- [Rosen, 1985a] R. Rosen. *Anticipatory Systems*. Pergamon, New York, 1985.
- [Rosen, 1985b] R. Rosen (ed.). *Theoretical biology and complexity*. Academic Press, Orlando, 1985.
- [Rosen, 1991] R. Rosen. *Life Itself*. Columbia University Press, New York, 1991.
- [Rosenblatt, 1958] F. Rosenblatt. The perceptron: a probabilistic model for information storage and organization in the brain. *Psychological Review*, 65(6), 386408, 1958.
- [Ruiz-Mirazo *et al.*, 2004] K. Ruiz-Mirazo, J. Peretó, A. Moreno. A universal definition of life: autonomy and opened evolution. *Origins of Life and Evolution of the Biosphere*, 34(3), 323346, 2004.
- [Ruiz-Mirazo and Moreno, 2004] K. Ruiz-Mirazo and A. Moreno. Basic autonomy as a fundamental step in the synthesis of life. *Artificial Life*, 10(3), 235-259, 2004.
- [Ruiz-Mirazo and Moreno, 2006] K. Ruiz-Mirazo and A. Moreno. On the origins of information and its relevance for biological complexity. *Biological Theory*, 1(3), 227229, 2006.
- [Rumelhart and McClelland, 1986] D. E. Rumelhart and J. L. McClelland (eds.). *Parallel Distributed Processing*, Vol. 1. MIT Press, Cambridge, Mass., 1986.
- [Ryan, 2007] A. Ryan. Emergence is coupled to scope, not level. *Complexity*, 13(2), 67-77, 2007. Pre-print available at <http://arXiv.org/abs/nlin/0609011>.
- [Salthe, 1985] S. N. Salthe, *Evolving hierarchical systems: their structure and representation*. Columbia University Press, New York, 1985.
- [Salthe, 1989] S. N. Salthe. Self-organisation of/in hierarchically structured systems. *Systems Research* 6, 199-208, 1989.
- [Sapp, 2003] J. Sapp. *Genesis: the evolution of biology*. Oxford University Press, Oxford, 2003.
- [Sawyer, 2005] R. K. Sawyer. *Social emergence: societies as complex systems*, Cambridge University Press, Cambridge, 2005.

- [Scheffer *et al.*, 2002] M. Scheffer, F. Westley, W. Brock, M. Holmgren. Dynamic interaction of societies and ecosystems — linking theories from ecology, economy and sociology. In L. Gunderson, C. Holling (eds.), *Panarchy: Understanding Transformations in Human and Natural Systems*. Island Press, Washington, 2002.
- [Schreckenberg and Wolf, 1998] M. Schreckenberg and D. E. Wolf. *Traffic and Granular Flow*. Springer: Singapore, 1998.
- [Scott, 2004] A. Scott. *Encyclopedia of nonlinear science*. Routledge, London, 2004.
- [Shalizi, 2001] C. R. Shalizi. Causal architecture, complexity and self-organisation in time series and cellular automata. Phd thesis, Physics Department, University of Wisconsin, Madison, 2001. Available at <http://www.cscs.umich.edu/~crshalizi/thesis>.
- [Shalizi, 2004] C. R. Shalizi, K. L. Shalizi, R. Haslinger. Quantifying selforganization with optimal predictors. *Physical Review Letters*, 93(11), 118701, 2004. Available at <http://arXiv.org/abs/nlin/0409024>.
- [Shalizi, 2006] C. R. Shalizi. Methods and techniques of complex systems science: an overview. In T. Deisboeck, J. Kresh (eds.), *Complex systems science in bio-medicine*. Springer. New York, 2006. Also available at <http://arXiv.org/abs/nlin/0307015>
- [Shapin and Schaffer, 1985] S. Shapin and S. Schaffer. *Leviathan and the AirPump: Hobbes, Boyle, and the Experimental Life*. Princeton University Press, Princeton, 1985.
- [Shi, 2001] Y. Shi. *Economics of scientific knowledge: A rational choice neo-insitutionalist theory of science*. Edward Elgar, London, 2001. PhD thesis, 2000, Philosophy Department, University of Newcastle, Australia.
- [Shipman, 1992] J. Shipman. Aspects of computability in physics. *Proceedings, Workshop on Physics and Computation*, IEEE, 299-314, 1992.
- [Simon, 1947] H. Simon. *Administrative behavior: A Study of DecisionMaking Processes in Administrative Organizations*. Free Press, New York, 1947.
- [Simon, 1969] H. Simon. *The sciences of the artificial*. MIT Press, Cambridge, Mass., 1969.
- [Simon, 1997] H. A. Simon. *Models of bounded rationality, vol.3*. MIT Press, Cambridge, Mass., 1997.
- [Skewes and Hooker, 2009] J. Skewes and C. A. Hooker. Bio-agency and the problem of action. *Biology and Philosophy*, 24(3), 283-300, 2009.
- [Smithers, 1995] T. Smithers. Are autonomous agents information processing systems? In L. Steels, R. A. Brooks (eds.), *The Artificial Life Route to 'Artificial Intelligence': Building Situated Embodied Agents*. Erlbaum, Hillsdale NJ, 1995.
- [Smolensky, 1988] P. Smolensky. On the proper treatment of connectionism. *Behavioral and Brain Science*, 11, 1-74, 1988.
- [Solé *et al.*, 2002] R. Solé, I. Salazar, J. Garcia-Fernandez. Common pattern formation, modularity and phase transitions in a gene network model of morphogenesis. *Physica A*, 305, 640-647, 2002.
- [Solé and Bascompte, 2006] R. Solé and J. Bascompte. *Self-organization in Complex Ecosystems*. Princeton University Press, Princeton, 2006.
- [Sperry, 1969] R. W. Sperry. A modified concept of consciousness. *Psychology Review*, 76, 532-536, 1969.
- [Sperry, 1986] R. W. Sperry. Macro versus microdetermination. *Philosophy of Science*, 53, 265-275, 1986.
- [Sperry, 1987] R. W. Sperry. Consciousness and causality. In R. L. Gregory (ed.), *The Oxford Companion to the Mind*.S Oxford University Press, Oxford, 164166, 1987.
- [Sterelny, 2007] K. Sterelny Social intelligence, human intelligence and niche construction. *Proceedings of the Royal Society*, London (Series B), 362(1480), 719-730, 2007.
- [Stewart and Golubitsky, 1992] I. Stewart and M. Golubitsky. *Fearful Symmetry. Is God a Geometer?* Blackwell, Oxford, 1992.
- [Stewart and Mossio, 2007] J. Stewart and M. Mossio. Is “Life” Computable? On the Simulation of Closure under Efficient Causation, Proceedings of the 4th International Conference on Enactive Interfaces, Grenoble, France, 271-276, 2007.
- [Strogatz, 2001] S. Strogatz. Exploring complex networks. *Nature*, 410, 268-277, 2001.
- [Sullivan, 2009] J. A. Sullivan. The multiplicity of experimental protocols: a challenge to reductionist and nonreductionist models of neuroscience. *Synthese*, 167, 511-539, 2009.
- [Szathmáry, 2005] E. Szathmáry. Life: in search of the simplest cell. *Nature*, 433(3 Feb.), 469470, 2005.

- [Tan *et al.*, 2006] P.-N. Tan, M. Steinbach, V. Kumar. *Introduction to data mining*. Addison-Wesley, New York, 2006.
- [Toulmin, 1972] S. Toulmin. *Human understanding*. Princeton University Press, Princeton NJ, 1972.
- [Truhlar, 2008] D. G. Truhlar. Editorial: Molecular Modeling of Complex Chemical Systems. *Journal of the American Chemical Society*, 130(50), 16824-16827, 2008.
- [Ulanowicz, 1997] R. E. Ulanowicz. *Ecology: the Ascendant Perspective*. Columbia University Press, New York, 1997.
- [Ulanowicz, 2003] R. E. Ulanowicz. On the Ordinality of Causes in Complex Autocatalytic Systems. *Annals of the New York Academy of Science*, 988, 154157, 2003.
- [Van Fraassen, 1989] B. Van Fraassen. *Laws and Symmetry*. Oxford University Press, Oxford, 1989.
- [van Zijderveld, 2007] E. J. A. van Zijderveld. MARVEL: Principles of a method for semi-qualitative system behaviour and policy analysis. Proceedings, 25th International System Dynamics Conference, Boston, 2007. Available at <http://systemdynamics.org/conferences/2007/proceed/papers/VAN{%-}20Z213.pdf>
- [Vapnik, 1995] V. Vapnik. *The nature of statistical learning theory*. Springer, New York, 1995.
- [Varela, 1979] F. Varela. *Principles of biological autonomy*. Elsevier, New York, 1979.
- [Varela *et al.*, 1974] F. Varela, H. R. Maturana, R. B. Uribe. Autopoiesis: the organization of living systems, its characterization and a model. *Biosystems*, 5, 187-196, 1974.
- [Vygotsky, 1986] L. S. Vygotsky. *Thought and language*. MIT Press, Cambridge Mass., 1986.
- [Walter, 1950] W. G. Walter. An imitation of life. *Scientific American*, 182(5), 42-45, 1950.
- [Walter, 1953] W. G. Walter. *The Living Brain*. Duckworth, London, 1953.
- [Ward, 2002] L. M. Ward. *Dynamical Cognitive Science*. MIT Press, Cambridge MA, 2002
- [Westerhoff and Palsson, 2004] H. Westerhoff and B. Palsson. The evolution of molecular biology into systems biology. *Nature Biotechnology*, 22, 1249-1252, 2004.
- [Wiener, 948] N. Wiener. *Cybernetics: Or the Control and Communication in the Animal and the Machine*. Paris, France: Librairie Hermann & Cie, and MIT Press, Cambridge, MA, 1948.
- [Wimsatt, 1999] W. C. Wimsatt. Genes, memes and cultural hereditary. *Biology and Philosophy*, 14, 279-310, 1999.
- [Wimsatt, 2007] W. Wimsatt. *Re-engineering philosophy for limited beings*. Harvard University Press, Cambridge, Mass., 2007.
- [Winfree, 1987] A. Winfree. *When Time Breaks Down*. Princeton University Press, Princeton, 1987.
- [Woese, 2004] C. Woese. A new biology for a new century. *Microbiology and Molecular Biology Reviews*, 68(2), 173-186, 2004.
- [Wolfram, 2002] S. Wolfram. *A new kind of science*. Wolfram Media, Champaign Ill., 2002. See also <http://www.wolframscience.com/thebook.html>
- [Zhou and Chen, 2003] Z-H. Zhou and S-F. Chen. Evolving fault-tolerant neural networks. *Neural Computing & Applications*, 11(34), 156160, 2003.