FROM FORMAL MACHINE TO SOCIAL COLONY:
TOWARD A COMPLEX DYNAMICAL PHILOSOPHY OF SCIENCE

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I. Introduction

We are naturalists aiming to ground philosophical notions in real dynamical processes. From our perspective science is better modeled as a dynamical system than as the formal logical (inductive and dedcutive) machine found in the work of both the rationalists and empiricists (Hooker 1991, 1995). We seek a model of science whereby accepted theory, practice and phenomena develop in mutual dynamical interaction; these, in turn, interacting with institutional organisations as well as our normative models of them. Only a dynamical conception of norms, we claim, is able to properly encompass the fundamentally social and historical nature of science while acknowledging the role played by the psychological capacities of individuals, all of which are sundered from it in the usual static formal models.

In pursuit of this conception we have elsewhere examined a range of traditional positions to reveal their tacit dynamical implications or implicit underlying models (Herfel and Hooker 1996). The most promising is Kuhn's explicitly dynamical account (1962), which is analogous to a re-organisational model of science with constant global ordering rules (normal science) interrupted by sharp, self-organised and disruptive phase transitions in which the ordering rules dissolve and reconstitute themselves in a different global pattern (revolutions). Though useful, the "phase transition" model of scientific revolution is crude, because: (1) Historical changes in science are much more complex (Hooker 1995; Herfel 1990), (2) it is difficult to know how to adapt the physical model to the sociological situation (especially since the physical situation itself is so poorly understood), and (3) phase transition is just one type of phenomenon available within nonlinear dynamical systems. Already in such innocuous inorganic models as the Bénard system we see rich dynamical features and one of us has argued (Herfel 1996) that such nonlinear dynamics are also typical of science, while the other has argued (Hooker 1995) that the science-technology system is a non-linear dynamic system sharing many of the distinctive characteristics of living systems, which centrally display these same features. Before showing how the unique properties of nonlinear dynamic systems prove pertinent to dynamical accounts of science (Section III), we explore just one such model (for want of space).

II. Investigating models for science: some lessons from the social amoebae.

Living creatures are highly interactive non-equilibrium systems stabilised by flows of energy through them, and so therefore are communities of them. A well documented organic process in which an energetic constraint enables novel behaviour is aggregation and differentiation of the cellular slime mould, *Dictyostelium discoideum*. Cellular slime mould*s* can exist both as uni-cellular, and as multi-cellular, organisms. When there is plenty of food (they live off bacteria), they exist as single celled amoebae. When starved, however, individual cells do not die; rather, they respond to this constraint (Nicolis 1989, 326)--a reduction in energy throughput--by organizing in circular wave patterns around, and streaming toward, a single organization centre. They then form a compact aggregate which grows upward, secretes a slime sheath, tumbles over and becomes a slug-like creature which crawls away, following environmental cues, toward a more favourable location where it again transforms itself, growing a fruiting body supported by a stem to drop spore cells producing new amoebae. This latter phase is marked by cytological, not only functional, cell differentiation.

Here we consider just the onset of the aggregation process. Aggregation requires a coordination of movement, in turn requiring a communication medium, now generally agreed to be cyclic adenosine monophosphate (c-AMP), which is known to increase in cells under the stress of glucose deficiency (Harold 1986, 478). The constraint to starvation enables the formation of aggregation by stimulating production of an excess of available c-AMP. The pulsatile secretion of the substance establishes a signal which the cells follow in order to meet at the point of aggregation. From an initially homogeneous amoebic distribution an organising centre forms and several models now exist which attempt to understand the dynamics of this process (Bazin and Saunders 1977; Garfinkel 1987; Gerisch 1986; Goldbeter and Martiel 1987; Keller 1985).

Characteristically, structure emerges from the imposition of a symmetry-breaking constraint on a system of non-linearly interacting components (here amoebae), which lose some freedom of motion in the process. In a nutrient-rich environment, each individual amoeba is an organized molecular system--hence one to which many complex constraints already apply--stabilized far from equilibrium by its food intake. In this condition the system is in a dynamical stability with its environment, and symmetric with respect to inter-amoebic interactions. Starvation represents a constrained departure from that dynamic stability, one which disables independence of individual movement but enables collective behaviour which would otherwise be inaccessible and which may ultimately by-pass the starvation constraint (Herfel 1997). This represents a higher degree of organization in the following sense: it allows the system to more effectively seek out the energy gradients that maintain its existence, a feature unique to biological organization (Wicken 1987), and a deep example of what Pattee (1976) calls coordination of constraints. By increasing its global constraints on individuals it has freed up their capacity to cooperate and so provided the dynamical basis for a capacity either to feed independently or to aggregate, depending on environmental conditions. This simple adaptability enhances their capacity to act fittingly in a wider range of environments. (Here adaptability is expressed at population level, but often it is expressed at individual level through behavioural adaptability.)

Alan Garfinkel (1987) discusses various models of the dynamics of *D. Discoideum* aggregation, and proposes a framework for adapting the results of these models to understanding human socio-dynamics. He identifies two types of models, the field model of Keller and Segel (1970) and various individual cell models, e.g. Goldbeter and Segel (1977). He then goes on to apply the lessons learned from modelling the social amoeba to modelling the social dynamics of human societies. We will briefly explore this account.

Two problems with the Keller/Segel field model, both artifacts of linear stability analysis, are identified by Garfinkel (1987, 187): (1) The model cannot say what will happen after the onset of instability, (2) it cannot accurately predict the stabilities of real systems subject to finite perturbations (because it is confined to vanishingly small perturbations). Later, Garfinkel (1987, 203) points out that these difficulties can be overcome by employing *nonlinear* models of the aggregation process. (Goldbeter and Martiel 1987 provide one such model.) This strategy is the one adopted in the complex models of adaptive self-organisation that inspire our analysis. Even so, field models, being continuous, omit the discreteness of the amoebae system, especially its local signal timing interrelations.

Garfinkel (1987, 190-200) then goes on to identify several aspects of aggregation left out of the individual cell model. These include: accurate details of wave dynamics, explanation of the emergence of ("autonomous") aggregation "centres", entrainment in the aggregation field and the various macro morphologies exhibited under varying aggregation conditions. In theory, one could construct more powerful models based on the dynamics of individual cells; in practice, however there are good reasons to believe that an accurate representation of these phenomena will remain elusive to the individualistic approach. After sketching the general features that such an *individualistic* super-model would possess, Garfinkel (1987, 201) remarks of it: "The model would be, mathematically, completely intractable, and nothing can be said about it. The complexity involved is at least that of the general problem of the entrainment of *N* oscillators, on top of the problem of pattern in reaction-diffusion systems added to the *N*-body motion problem. Any *one* of these problems is insuperable in general form; simultaneously they render the analytic situation hopeless." After showing that employing some of the standard simplifying assumptions largely used in overcoming such difficulties would amount to throwing the baby out with the bath water (Garfinkel 1987, 201), Garfinkel (1987, 203) concludes that "... we are forced to adopt a field-theoretic, rather that a particle-theoretic, model of the self-organization process."

We note, however, that there are now many seminal models of non-linear dynamics based on the generation of complex global dynamics from iterated interactions among elements obeying just a few global constraints and local interaction rules. (See work by those in the Santa Fe Institute, e.g. Arthur 1994; Forrest 1991, and references therein.) We do not know whether Garfinkel considers such models "individualistic" (since he doesn't discuss them in his work with which we are familiar), but if so, we part company with his dismissal of individual-based models. We suspect that a grand unified theory of non-linear dynamics is not going to be easily forthcoming--possibly not at all--for exactly the kinds of reasons Garfinkel gives for the insolubility of the N-oscillator problem. But whether an individual-based approach or a global field model will be most useful will most likely depend upon context. Garfinkel should agree with this observation, given his remarks concerning "explanatory relativity" in his (1981).

Garfinkel outlines a framework for applying his conclusions from the modelling of slime mould aggregation to social structure: explaining cooperation in the prisoner's dilemma and emergence in economics. We cannot explore these specific issues here, but move to the key themes that he considers to have emerged from the self-organization paradigm, namely holism and symmetry-breaking, which assert the essential dynamical roles of global system variables, constraint and coherence conditions and attractors, and catastrophe and bifurcation, which "give a richer scientific content to the notion of emergence and make possible models of physical, biological, and social processes in which periods of continuous change are punctuated by episodes of emergence" (Garfinkel 1987, 210). And, following Garfinkel here, we would add the concepts that seem essential in discussing aggregation in the slime mould, especially the notions of oscillation and entrainment. Entrainment, in the form of interactive coherence among actions, seems to be a crucial concept in understanding the evolution of social, as well as biological, organisation; aggregation and cooperation. "In the future the *N*-torus may be as familiar a model for biological or social space as Euclidean space is now, with pattern formation expressed in terms of various forms of oscillatory entrainment or coherence" (Garfinkel 1987, 210).

III. *A framework for modeling science as a system of nonlinear interaction.*

We use the themes suggested by Garfinkel's work, and that of others (e.g. those in the Santa Fe Institute, see above) to develop a cluster of concepts apt to applying nonlinear dynamics to social systems, with an eye toward treating the socio-cognitive structure of science. For each, we first present the general dynamical property and then briefly discuss its application to science.

1. *Local non-linear interactions + non-equilibrium constraints yield global complexity.* In the slime mould case complex and highly organised global dynamics are generated by non-linear interactions among local elements (amoebae), combined with the application of local and global constraints. The interactions are expressed in terms of one or a few well defined local interaction rules, here rules for generation of c-AMP and streaming, which gives rise to the necessary macroscopic property of co-ordination. The constraints are both local and global, and this is necessary as far as we can see, and while many of them may contribute to establishing the initial stable state, at least one must constrain the system away from that equilibrium. By contrast, the erstwhile dominant approach to modelling science has been to reduce interactions to a few simple logical rules, Scientific Method, the same for everyone, which would in principle treat all scientists identically as but local ciphers for a single global state of science. This analytic ideal is now increasingly rejected, and here we see that it is also deeply inadequate to the dynamical character of science, resulting in a false set of questions and problems. Instead we can quite properly expect the interaction rules to vary from context to context, within and without epistemic institutions, and over time as scientists learn about improving methods as they improve data and theories. (See Herfel 1996; 1997; Hooker 1991; 1995 for some elaboration.) Science actually comprises a system of individual scientists interacting non-linearly (e.g. changing each others beliefs and behaviours), subject to a set of institutional role constraints (e.g. laboratory procedure, journal reporting and refereeing conventions) and supported by, i.e. constrained away from equilibrium by, a flow of resources (energy, goods, services, money) through it. In this it is like any other social activity, a (far) more complex version of our social amoebae. But to the degree they apply, its particular institutional constraints differentiate it from other social activities and are what give it the design of an epistemic institution (e.g. Hooker 1995, Latour 1986, and references). It is these interactions which, in combination with institutional roles, generate macro scale properties like research tradition, disciplinary grouping, cultures of criticalness and the like which are essential for science to proceed.

2. *Amplification.* Nonlinear dynamic systems can exhibit "initial conditions sensitivity": the effect of very small events (variations, fluctuations) can become rapidly amplified to more global scales and fixed there by the energy flows in the system, so that their ordered structures thereafter play essential roles in the system's dynamics. In our example, small local timing coordinations in c-AMP emission were amplified to macro scale. Oscillatory entrainment is one of the prominent ways in which small correlations may become amplified to more global scale and fixed there. Science too shows "initial conditions sensitivity": the details of the macrostructure of science can be sensitively dependent on activity changes by individual scientists (micro variations) and thereafter play an essential role in the scientific system's dynamics. Watson and Crick's discovery of DNA structure (Watson 1968), e.g , applied a developing experimental technique (Xray crystallography) to a new domain and its results were amplified (using the resource flows) to widespread (macro scale) acceptance producing a new coordination (entrainment?) of subsequent activity. Just this

phenomenon of micro to macro amplification lies behind all scientist's hopes of making a recognised discovery, and the "damping out" of one's new invention because it does not stand scrutiny (or worse, because it is drowned by the sheer volume of "noise" in the system) is at the root of their fears.

3. *Self-organisation, symmetry breaking and resource flows*: Our example system shows the spontaneous emergence of structure through symmetry breaking as it is constrained away from an equilibrium by alteration of energy flow through it. This is a characteristic consequence of genuine self-organisation. (A dynamical symmetry in some property P means that the system dynamics is invariant over variations in P, here amoebic interaction, random movements and metabolic state; hence the system cannot constrain P changes - they are spontaneous for the system - and they dissipate to equilibrium with the system environment. The self-organisation process is distinguished by the production of new macroscopic order from that in some initial small P variation through amplification and so represents a symmetry breaking - Collier 1996, Stewart and Golubitsky 1992.) One pervasive form of this process is that of variation, selection and retention (VSR), where the variation is some spontaneous (i.e. system uncontrolled) symmetry-breaking production of variants amplified to macro scale, the selection discriminates one of them and retention summarises the result of its amplification, e.g. in evolution. Similarly, science has had increasingly large resource flows directed into, and through, it over the past 400 years, and corresponding to this has been the emergence of ever wider and more differentiated institutional and cognitive structures. Each emergence of a new discipline, sub-discipline, tradition or research grouping creates a macro scale distinction where there was none originally and so breaks that previous socio-epistemic homogeneity (symmetry). Again, one pervasive form of this self-organisation is VSR, developed as evolutionary epistemology (Hahlweg and Hooker 1989).

4. *Bifurcation.* Global transformation of dynamical form resulting from broken symmetries is also characteristic of their self-organisational capacities. In the self-organisation of new global order the system does not simply utilise its existing macroscopic dynamical laws to reorganise itself but transforms them through the introduction of new kinds of internal constraints. Our amoebae lose some individual freedom to move independently while the system gains organisational freedoms, to collectively move about and even fruit, it did not formerly possess. The symmetry-breaking amplification to macro acceptance of a new scientific concept or procedure, bringing new macro coordination constraints, establishes a new dynamics to science, a bifurcation, in which scientific experiments, methods, criteria, and communication and/or alliance patterns change somewhat thereafter in ways that are not just shallow logical re-organisation to accommodate new but compatible information. The very large scale and organisationally deep changes we call scientific revolutions, but these can only be distinguished by their dynamical effects from other complex but shallower changes occuring all the time (Hooker 1995).

5. *Varieties of constraints and adaptiveness*. Tighter constraint does not necessarily impoverish behaviour but, as we have just illustrated, may instead enable the emergence of new forms of previously inaccessible behaviour. A pedestrian example is provided by organisms: adopting phosphate as an energy source; this puts severe constraints on what can be eaten, but it is central to enabling all the distinctive attributes of living systems. Constraints can be local or global, deterministic or stochastic, static or time-varying and, most importantly, enabling as well as

disabling. (Herfel 1996 argues that nonlinear dynamics are best thought of as the result of progressive application of constraints with full blown determinism being recovered by constraint to a unique allowed path.) It is through the coordination of constraints to form enabling constraints (see Herfel 1997 for an extended discussion of enabling constraints) that living systems have developed both specific adaptations and adaptability. In science it is precisely the institutionalised procedural constraints (e.g. experimental technique or mathematical modelling) that enable scientists to explore the natural world so successfully. Though they restrict individual degrees of freedom, it is these institutional constraints which are essential in enabling scientists collectively to pursue science without it falling into an incoherent bable of differing, or corrupt, voices, despite the fact that individual scientists know in any detail a tiny fraction of their own discipline, let alone science as a whole. Science is a highly adaptive system because of its institutionalised sensitivity to environmental information (results, data) and commitment to incorporating that information into its future activity modes (Hahlweg and Hooker 1989). It is through the co-ordination of its institutionalised constraints to form enabling constraints that it expresses its adaptiveness.

6. *Non-additivity and emergence*. Solutions to mathematical models of nonlinear dynamical systems are non-additive, and for this reason their dynamics is non-decomposable (i.e. not derivable from local models of the individual constituents themselves), leading to genuine, because dynamically grounded, emergence. While two-body gravitational systems can be shown analytically to be stable and periodic, even three-body systems are capable of dynamical chaos, this latter possibility emerging by simply adding one more body to the system, with no change in fundamental physical law. We expect that all examples of emergent phenomena, for instance, life and intelligence, can be dynamically explained in specific similar ways. Science dynamics too are non-decomposable, showing the genuine emergence of new macro scale features not derivable solely from local models of individual scientists - see e.g. the results of the interaction of the hitherto separated bio-chemical and X-ray crystallography fields in the DNA case above. A similar situation obtained between scientific and practical technological investigation of flight, the latter making deep differences to the former, and reminding us that we are really discussing the science-technology system throughout.

7. *Irreversibility, path-dependence and historicity*. A non-linear dynamic system is characteristically macroscopically irreversible. Although the structure of its dynamics is determined by micro-level events, information about the exact nature of these events is lost at the macro scale as it evolves through self-organisation and is not recoverable by running a macroscopic model of it in reverse. Such systems become "locked-in" to the particular path that was initiated by a succession of amplified small events, its future behaviour thus path-dependent and constrained by its historical development. In such cases we can only understand why the system has come to be in the state or attractor that it is in by studying it historically (ee Arthur 1994 and Stanford colleagues for an aplication of this insight in economics). Although science's dynamics is determined by local actions of individual scientists (micro-level events), information about the exact nature of most of these actions is lost at the macro scale (e.g. in journal papers) and is not recoverable by running a macroscopic model of it in reverse. Science is also irreversible because its epistemic character leads it to being both accumulative and revolutionary, again the details are typically sensitively dependent on activity changes by individual scientists and lost at the public macro scale. Once macroscopic structure emerges the system is typically "locked-in" to using it thereafter as a base for new work

(cf. Wimsatt and Shank 1988 and, informally, Latour 1987). In consequence, the science(-technology) system is path-dependent and thus typically constrained by its historical development and it must be studied historically to understand it.

8. *Constraint duality and super-system formation.* The dynamical structures that emerge in non-linear macroscopic bifurcation express constraint duality: emergent global structure constrains the behaviours of individual elements as genuinely as their interactive dynamics constrained its formation and continues to sustain it. Top-down constraint occurs simultaneously with bottom-up constraint. While a population is "nothing but" a collection of organisms, an organism may develop in a variety of ways, depending on the physical and social environmental constraints, even while it in turn influences other organisms and alters the physical environment. Each dynamically grounded top-down constraint gives added force to the formation of a genuine super-system from the collection of interacting system elements; the amoebae, e.g., form an increasingly clear super-system as they first aggregate and move coherently and then differentiate. The structures that emerge in scientific macroscopic bifurcation similarly represent genuine global constraints on the local behaviours of scientists; whose roles thereby lose one or more of their degrees of freedom (Herfel 1997). This expresses scientific constraint duality: the various more global structures of science then constrain the behaviours of individual scientists as genuinely as their interactive dynamics constrained its formation and continues to sustain it. Top-down constraint occurs simultaneously with bottom-up constraint. Each dynamically grounded top-down constraint gives added force to the formation of a genuine science super-system from the collection of interacting scientists.

To these we add two further features which concern shifts in the fundamental ways we are able to understand these systems. Hitherto we have derived our paradigms for understanding from simple systems, e.g. a single Newtonian particle, for which a complete universal global model exists. Thus completeness (all features simultaneously, analytically represented), universality (applies in all circumstances, e.g. across all constraints, within the theory's domain of application, ideally everywhere) have formed our ideal criteria for understanding. But these ideals seem unachievable in principle for non-linear dynamic systems.

9. *Model specificity/model plurality.* Given its foregoing features, we do not expect a unified theory of nonlinear dynamics to emerge. The characteristic behaviours of nonlinear dynamical systems all derive from systems configuration, parameter values, and boundary conditions, not solely from the operation of its interaction laws. Hence these models must all be specific to the conditions of the phenomena being modelled, and, given dynamical bifurcation between conditions, a plurality of differing, though variously dynamically interrelated, models will generally be required to understand all the complex phenomena exhibited by systems. Consequently, we cannot expect there to be a grand unified theory of science of the simple deductivist kind idealised by formal logical models. The characteristic behaviours of science derive, not from psychological peculiarities of scientists as humans or of their kinds of interactions, all of which apply throughout social life, but from institutional role designs and their supporting norms. Hence these models must all be specific to the material and social conditions of the phenomena being modelled, and a plurality of context-sensitive models will generally be required to understand all the complex phenomena exhibited by science - though the complex global coherency requirements peculiar to science will generate a corresponding set of interrelationships among these models. (Hooker 1996 employs ecological genome

interrelations as a model for this sort of unity.)

10. *Model centredness.* Typically, non-linear dynamical systems have no analytic solutions, or even analytically constructible descriptions of their pertinent dynamical behaviours, or at least none we currently know how to construct. Given the kinds of problems to overcoming this Garfinkel cites (see his last quote above), this circumstance is likely unavoidable in principle. Wherever analytic solutions or characterisations fail we have no recourse but to iterative numerical modelling to explore the dynamics. This represents a striking new feature to theoretical science, the ineliminability of concrete, specific modelling to even specify, let alone understand, the phenomena (Herfel 1995). We equally have no analytic models of the dynamics of science; certainly not over time because future knowledge is in its nature unpredictable, nor across science because the macro consequences of local interaction are not derivable from them alone. We must study science as we have always done, historically, iterating by following sequences of interactions as they spread non-linearly through the system, generalising where possible. Every scientific transition is to some extent unique and must be understood on its own terms - but from this nothing follows about the abandonment of rationality, only of simple logical models of rationality (Hooker 1991).

IV. Conclusion: A manifesto for an integration of normative and dynamical models

Traditionally, one way philosophical accounts have been distinguished is by the fact that they are aimed at uncovering the normative bases for human activities. In philosophy of science this has amounted to prescribing a methodology of scientific practice. Since our account is so steeped in modelling the dynamics of science one may be lead to the conclusion that ours is a purely *descriptive* account. Certainly we believe that nonlinear dynamical models will assist in the creation of a more accurate and precise characterisation of the scientific enterprise. Nevertheless, ours in not *merely* a sociological exercise in the descriptive sense. First we should point out that the very notion of "pure description" is dubious (cf. Kuhn 1962 on theory-ladenness). From our perspective, understanding, philosophic as well as scientific, is a modelling process. Modelling requires assumption. Assumption requires value judgment. Value judgment requires normativity. But our point cuts deeper than this.

We are committed to the view that our norms emerge from practice and, conversely, regulate practice; so our understanding of norms must be grounded in a careful analysis of practice. Nonlinear dynamical models make intelligible processes in which norms are dynamically relevant, and show where, and how. Methods have constantly evolved in nonlinear interaction with theory and data, and just this is central to science (Hooker 1987, 1995). Methodological norms, e.g. laboratory procedures, are, and ought to be, based on empirical models of what is dynamically relevant and reliable. Hence there is neither a dichotomy between normativity and dynamics nor a reduction of one to the other. (Furthermore, we endorse reflexivity while maintaining the possibility of pluralism: one would expect that we can only learn about science through a careful modelling of the practice; however the modelling process itself must be informed by what is learned from the models.)

In this spirit one of us has proposed to replace the traditional formalist logical conception of reason with that of efficacious re-, and self-, organisation, applying to both individual scientists and to science (Hooker 1995). It is argued that this is a naturalist, dynamically grounded conception adequate to both the required normative role of reason and the dynamics of science. It can be fruitfully, if ultimately partially, modelled in terms of a decision theoretic approach to epistemology in which acceptances are practical actions made under a variety of utilities whose relative priorities properly differ across institutional contexts. Whether this will turn out to be the best approach is an open question.

We can imagine a range of possibilities for the normative bases upon which science has evolved, from crass economic gain at one extreme to the disinterested pursuit of truth at the other. Identifying the possibilities and attaching them empirically to portions of science, is only part of the task. In the long term we seek to evaluate the scientific process, with an eye toward improving it (to the extent that this is practicable). The norms that ought to be adopted are the ones that lead to intelligent and successful practice. So far there is no way to judge which norms will so lead without a clear understanding of their dynamical consequences. Within our framework at least this program is intelligible.

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