New perspectives on realism, tractability, and complexity in economics

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New Perspectives on Realism, tractability, and Complexity in Economics.

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Summary.

Mainstream economics owes its influence to three factors. (i) Its claim to show how unfettered market forces can optimise the allocation of resources. (ii) A model of motivation and behaviour that predicts advantages for a much-reduced role for the public sector. (iii) A very large, long-standing and ongoing public relations campaign, financed mainly by large business organizations, to promote these ideas as true and sound. Evidence is presented that the bases of (i) and (ii) are artefacts of the stringent process of simplification used to condense complex reality into simple models ('complex' and 'simple' are defined).

In the former case, fuzzy logic and genetic algorithms are used to rework a more realistic (and more complex) version of the basic model of competitive markets, resulting in an equilibrium significantly different from the one predicted from the usual static analysis, and which is not compatible with the theorems about the optimality of competitive equilibria. This study also shows that, with methodology that demands much less stringent simplification, the Walrasian problem of how a market could attain equilibrium is readily solved.

In the case of (ii), research in the fields of management, political science, theoretical and field biology, and in neuroscience shows that the belief that economic rationality will necessarily drive actors in politics and the public sector to misbehave in ways that give the private sector an inherent, strong advantage in efficiency and effectiveness is wrong.

The possible extension of the methodology applied to (i) to other technical aspects of economics (including international trade theory, and development), and the limitations to usefulness of theory in political domains, are both discussed; the philosophical case for

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laissez-faire policies is considered briefly; and the prospects for change in the way we view the economic domain are reviewed.

1. Introduction.

The field of political economy is currently dominated by mainstream economics (MSE), which consists of two parts. Its core – which gives it intellectual respectability – is the body of theory and assumptions that support the conclusion that market forces, on their own, are capable of ensuring that our resources are, in some reasonable sense, put to the best possible use, nationally or globally. A specific and very simple model of motivation and organizations underpins this core; and this has developed into the second element of MSE, which takes its purest and most extreme form in public choice theory (this is discussed later). It is difficult to over-estimate the influence of this combination. Its influence on public administration and development is particularly strong, and this is reflected, for example, in the way that 'public sector reform' is defined, and in claims that freeing-up the international markets for goods, services, and capital is a necessary and sufficient condition for improving the lot of the world's poor.

However, it is equally difficult to ignore the critics of MSE. Some focus on mitigating the human consequences of MSE, which they judge to be unacceptable; in the UK, New Economics Foundation and the Green Economics Institute are examples of institutional critics of this school. Unfortunately, this form of criticism seems to have failed to generate any dialogue with those who are convinced that this strong form of MSE represents the world sufficiently well for most (or even all) policy purposes. Others attack weaknesses in the internal logic of the MSE case. For a summary of these internal criticisms, see [1]; many of these critics are leading figures within the economics profession, who are cautious about over-emphasizing the optimising power of market forces. However, they also appear to despair of finding methods that can handle more realistic versions of key economic questions; international trade, income distribution, and development are the most important of these.

This paper develops a third line of criticism: that the core models of MSE are over-simplified to the extent that they cannot reproduce many phenomena that are important in real economies, and they are therefore likely to generate misleading policy prescriptions. This style of criticism dates back to Schumpeter's complaints about the ‘Ricardian Vice’, i.e., the construction of models that exclude significant aspects of the problem in the interests of mathematical tractability [2]; and there is an important dissenting tradition in economics that is deeply concerned about this [3]. However, it is only very recently that tools that can handle the additional complexity of more realistic models have become available.

This last type of criticism – which this essay attempts to elaborate – has a constructive aspect. It implies that some fairly specific enhancements to our conventional toolkit are needed, and one approach to providing this additional capability is demonstrated below, where the relevant methodology (detailed in Section 4) is applied to the most fundamental of the core models (that of perfectly competitive markets). This methodology does not require such stringent simplification of reality to ensure tractability; and the results of applying it are substantially different from the standard ones. The essay also attempts to link this research with other work (based on similar methods) that impinges on mainstream models of motivation and organizations. Taken together, this body of work and ideas shares a significant feature of MSE: it claims not only to provide a framework for technical economics, but also to provide models of motivation, management, and institutions. These two perspectives differ in fundamental ways that affect much of economic practice and theory-building; the essay concludes with a brief comment on this, and the prospects for change.

2. The Assumptions: Complexity versus Simplicity.

The real world is complex, in the very specific sense explained below, whereas the core models of MSE (of competitive markets, international trade, etc) are simple, in an equally specific sense (and despite their mathematical sophistication). Simple systems are static or have linear dynamics (and therefore have no threshold effects, tipping-points, or positive feedback, etc.) We understand them perfectly and completely; their key variables are all quantitative; and, while they may be subject to risk, that is also quantifiable and stable. In simple systems, causal chains are short and unidirectional, and transactions of all kinds can take place instantaneously; in the simple models used in MSE, time is either ignored entirely, or it is treated as strictly continuous, and any memory effects are assumed to be short and simple in form [4]. If simple models contain more than one agent, those agents are identical.

Complex systems differ from simple ones, in all these features. They have nonlinear dynamics. At best, our understanding of them is approximate; and some or all of their key variables are qualitative. They may be subject to quantifiable risk, but they are also subject to more radical kinds of uncertainty, some of which arises from our ignorance; this is the kind of uncertainty that both Frank Knight and John Maynard Keynes were concerned about [5]. Some uncertainty also derives directly from nonlinearity: nonlinear processes quite often generate time-series data (for both natural and economic processes) that are marked by apparently causeless – and sometimes large – shifts in typical value and variability. They also show deviations from the average much larger than those predicted by the Gaussian[2] probability distribution usually assumed in mainstream work on risk; this often gravely understates the probability of ruinous events (sometimes by many orders of magnitude). These deviations are often associated with long memory effects [6, 7]; and they have contributed to a number of financial debacles, including the LTCM affair [8] (although other factors were also involved in that case).

The above-listed features combine to create ambiguity: historical data may prove misleading, and facts are often open to conflicting interpretations. The data on rational expectations – the doctrine that agents learn, rapidly and accurately, the properties of the economic systems in which they live, so that policy intervention is largely futile – provide a good example [9]. In complex systems, transactions and transmission of information take time (and it is usually calendar time – i.e., continuous time, with gaps for holidays, etc – that is significant). Cause-and-effect chains ramify extensively, and often contain indirect circular linkages. Populations of agents in complex systems are always heterogeneous. Fully complex systems often have emergent features, i.e., ones that cannot be predicted from knowledge of their

[2] 'Gaussian' is used here, rather than the usual description, 'normal'. Many real economic time series data are neither Gaussian nor 'normal', especially as far as the risk of extreme events is concerned. However, both the Gaussian distribution and the more realistic multi-fractal distribution described by Mandelbrot and Hudson (see [6]) are members of the same fundamental family, the *L-stable distributions*.

component elements [10]. However, even sub-complex systems (with only some of the above characteristics) often do not behave like simple ones. For example, models that rely on the assumption of strictly continuous time may fail to match the behaviour of the corresponding real systems (operating in calendar time) in important ways [11]. Ormerod (see [1]) also stresses the theoretical vulnerability of simple models to apparently minor, innocent deviations from reality.

Simple linear models do not, in general, reproduce the behaviour and properties of complex dynamical systems at all well; and while both real systems and their models can be complex, there are no real simple systems in economics or public policy.

3. The Questions Investigated.

Ultimately, all the core theorems of MSE are derived from models that are in a state of supply/ demand equilibrium. The question of how a given collection of firms and consumers *reach* equilibrium ('the issue of the Walrasian Crier') has never been properly resolved, even for the case of simple models [12]. If these equilibria are not actually attainable, their properties – however desirable – are irrelevant. (This is not a destructive quibble: many nonlinear dynamical systems can be shown to possess static equilibria which, however, cannot be reached from any credible starting point by any series of technically permissible steps [13]. Mathematical economists tend to acknowledge this possibility, but they then fail to address it in any but the simplest cases; see, for example, [14].) The outstanding questions are, then:

- What rules would intelligent, profit-driven firms choose to adopt, as a result of their experiences in an evolving market, to regulate their businesses in a complex environment?
- Do these rules differ from those attributed to firms in perfectly competitive markets?
- Do they result in equilibrium, and – if so – how similar is it to the one predicted by the standard model? (For example, is the equilibrium price different?)

(There is a more fundamental question of how the collection of consumers and firms that constitutes a particular market comes together in the first place; this is considered later.)

4. The Investigation.

The evolution of those sets of rules was simulated in a series of multi-agent models. The agents are of two types: consumers (500 in each model) who are identical, and who seek the cheapest sources of supply on a best-of-three-bids basis; and firms (initially 50) acting as suppliers, whose technical and financial endowments are heterogeneous.

Because the investigation concerns how a market price is established in the first place, the firms cannot be 'price takers' in the usual sense of reading the price from the market. Instead, they use rules to set asking prices in the light of market conditions, and/ or their commercial situations; and they revise these rules in the light of their impact on sales and profits. The rules are expressed in fuzzy logic (FL) notation. This is a consistent, rigorous logic, designed to formalize the human capacity of reasoning from qualitative and ambiguous information (see below). Firms are given the capacity to learn from experience, through a genetic algorithm (GA): this conserves rules that work well, and eliminates those that do not. (Firms start with sets of rules that are random but well-formed.)

The simulation was repeated on ten randomly-generated sample markets, each with conventional supply and demand functions (and, therefore, a known static equilibrium price), from which the individual supply and demand functions are generated. For each market, the learning process was repeated for six treatment combinations, comprising of all combinations of the following: two types of market dynamics, 'simple' and 'complex' (see below); and three levels of risk, low, moderate, and high[3]. (This is, of course, a standard factorial design, with two factors,

[3] Markets were generated by selecting a point in a box bounded by the quantities 0 and 100,000, and the prices 0 and 100 (arbitrary units), as the static equilibrium position, SEq. Random coefficients were chosen for quadratic supply and demand curves passing through SEq, subject to the requirements that the curves are monotonically increasing for positive supply and demand, and have price elasticities at

risk and dynamics, each at three levels, replicated ten times.) Each simulation allowed each agent, on average, to be modified by the GA twenty times; between each pass through the GA, firms were given a number of trading periods (usually 9) in which to accumulate experience of the performance of their current ruleset.

The 'simple' treatments mimic the standard model of perfect competition (with the unavoidable exception of using the asking-price mechanism). The 'complex' treatments are more realistic; the firms only make one decision (the asking price), but they have to manage all of its consequences, including plant replacement and cashflow. Firms can become bankrupt, and new firms can also enter the market if conditions are sufficiently attractive. In these treatments, both investment in plant and the birth of new firms lag behind the market signals that initiated them. It may now be helpful to look briefly at the principles of fuzzy logic and genetic algorithms, but those readers who are familiar with these, or are primarily interested in the implications of this work, may prefer to return to Sections 4.1 and 4.2 later.

4.1 Fuzzy Logic.

A variable may be fuzzy for one of two reasons. Firstly, there may be no meaningful way of measuring it quantitatively (this is often true of the physical consistency or smell of substances, see, for example, [15]). Secondly, the processes that generate it may be so complex and uncertain that there is no way of singling out a single numerical value as the 'right' one[4] (as there would be for a long, clean series of data from a Gaussian distribution, for example). Fuzzy logic (FL) can process propositions about systems and data that are fuzzy for either of these reasons. It does this by using membership values (MVs), which say *how good a member* of some set it is. MVs are determined by membership functions (MFs), which take some input, measured on a support scale[5], and convert it to a MV, which can range from zero (not a member at

SEq in the range [0.5,1.5]. Demand risk was generated through an auto-regressive, moving-average disturbance, sufficient to create a coefficient of variation of profit of zero, 5% , and 10%, for the three levels.

[4] This would be the case if the relevant probability distributions have non-stationary statistics, and very thick tails.

[5] Support scales can be qualitative. Such scales are very useful, for example, for providing a transparent, challengeable basis for a set of qualitative rules or assessments; however, they are not needed here.

all) to one (full and perfect membership). This is, of course, in direct contrast to conventional logic[6] (CL), which uses zero/ one truth-values that say *whether or not* an object or case is a member of a given set (e.g., whether or not Socrates is a member of the set 'mortal beings').

Figure 1 shows a set of MFs, which, between them, span the entire range of interest of a particular variable – in the case shown, the amount of unsold product held by a hypothetical firm. (MFs do not have to be triangular, but this is computationally convenient in many applications; when they are, the three defining points are called keypoints. A set of MFs does not have to form a neat pattern, as in the Figure, either.) Each function defines a fuzzy set which contains everything to which the MF assigns a non-zero MV.

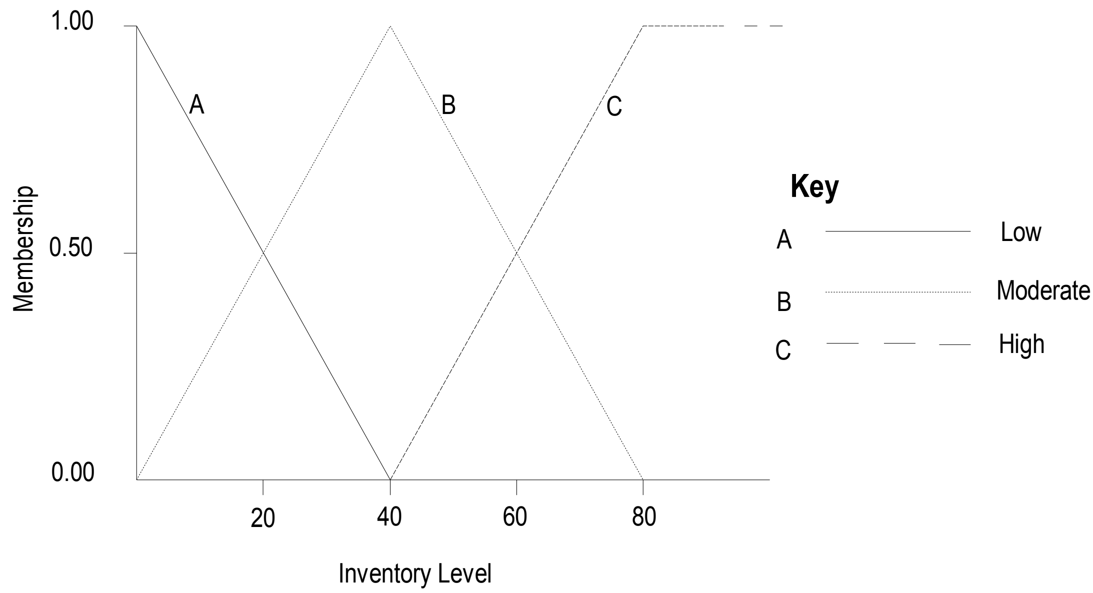

Figure 1: Membership Functions.

[6] Here, 'conventional logic' means two-valued logic, operating on mutually exclusive sets with precise boundaries.

Membership functions can be determined from: (i) special cases about which we have some theoretical knowledge; (ii) historical data; (iii) by calibrating the rules implicit in the actions of experienced operators; or (iv), as in this study, by optimisation through learning.

In the figure, the left-hand function, A (the membership function for *low inventory*), assigns a value of 1.0 to zero inventory, which is thus identified as a perfect member of this set. (Perfect members are sometimes referred to as type members, particularly if they are used to define the set. Often, they are chosen because they correspond to a situation about which we have some special insight or theoretical knowledge; zero inventory is special in this sense because it corresponds to equilibrium between demand and production.) As the actual, observed level of inventory increases, its membership in the set *low inventory* decreases (it ceases to be a member at all at forty units), while it becomes a better member of *moderate inventory*[7]. As the actual inventory level rises from zero to forty units, the contribution of A to the overall response from a fuzzy ruleset will decrease, and that of B will increase, because of the nature of the fuzzy inference procedure, see below.

In most applications, we are interested in a case's joint membership of two (or more) fuzzy sets. The membership of, say, a given case in the fuzzy set *low inventory AND high profit* is the lesser of its memberships in *low inventory* and *high profit*, considered separately[8]. Like single memberships, joint memberships (such as 'this is a case of *low inventory AND high profit*') are propositions that can be more or less true; and how true is measured by the membership value. As in all logics, propositions can be used to express inferences, such as

if inventory is *high* **and** profit is *very low*,

then the appropriate asking price is *low*.

The first two clauses ('antecedents' in CL) are referred to as *inputs* in FL; and the last (the 'consequent'), as *output*. For historical reasons, the consequent clause is usually be written '…**then** set asking price *low*', and the whole structure is referred as a rule.

[7] The names of fuzzy sets, and of the corresponding membership functions, are given in underlined italic throughout.

[8] 'AND' here operates in an analogous way to 'AND' in CL, where it selects the lesser of the truth values of two conjoined propositions.

(Its output is, of course, also a fuzzy set, see below.) One such structure cannot, of course, determine the output of a set of fuzzy rules from a single set of input data. Because of the overlapping of fuzzy sets, a given case will normally activate more than one rule; the output of each (active) rule is a modified form of its output membership function, and the inference procedure is defined in such a way that the overall output is a single figure, determined by what is, in effect, a weighted voting procedure. The numerical value of each rule's 'vote' is determined by the position of its output MF; but the weight of that vote is determined by how good an example the current situation is of the fuzzy set defined by the rule [16].

In CL, overlapping sets are forbidden[9]; any logic that is to embrace ambiguous and qualitative data has to relax this restriction, but this does not create any fundamental problems [*cf* 17 with 18]. Conventional logic is actually a special case of the fuzzy variety [19]; and the inappropriate use of the former in the domain of the latter, tends to produce dramatic but erroneous conclusions[10]. An important example in the context of MSE is the claim that there can be no valid *logical* basis for any interpersonal comparison of the satisfaction (or pain) experienced by individuals as the result of any act of consumption, or caused by any restraint on economic action – and therefore, of course, no justification for measures that seek to alleviate severe suffering among one set of individuals, by imposing relatively small pains on another, e.g., through taxation; see Box 1.

In the study described, each firm had a set of fuzzy rules governing its response to commercial/ market conditions. Each rule had two inputs, the levels of profit and inventory, and one output, the asking price. (Preliminary investigation had suggested that these two variables were the most effective pair.) The rulesets covered all combinations of 3 fuzzy levels of inventory and 5 fuzzy levels of profit, each set thus consisting of fifteen rules in all.

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[9] By the laws of non-contradiction and excluded middle: nothing may be, say, both black and not-black; and nothing may be neither black nor not-black. We do, of course, violate these extensively in everyday (fuzzy) reasoning.

[10] Bertrand Russell, in *The History of Western Philosophy*, remarked (of Hegel) that 'the worse your logic, the more interesting the consequences to which it gives rise'.

Box 1.

Fuzzy Logic versus Conventional Logic in Interpersonal Comparisons.

In conventional logic, if I assert that I can compare the pain of *M*, whose right to buy caviar is circumscribed by taxation, with that of *N*, who cannot afford medication to treat his daughter's TB, I have to be prepared to defend my ability to make such comparisons in every case (less sardines for *M, versus* more gooseberry jam for *N*, and so on.) In CL, a pattern of reasoning is either universally valid, or universally fallacious: the truth of an argument is guaranteed by its formal structure. We can, for example, infer from *All men are mortal* and *Socrates is a man* that *Socrates is mortal*, solely because it belongs to the valid pattern:

All A are X… *N is an A…* *therefore, N is X*.

The caviar/ TB example is problematic, precisely because it breaches CL's requirements for this kind of formal validity, and for its subject matter to consist exclusively of crisp sets (non-overlapping, with precise boundaries, and whose members can always be classified with certainty). To justify my original assertion, and to base a case for redistribution on it, CL would insist that I can show that the following argument belongs to a valid pattern of reasoning: *All severe suffering justifies redistribution… This is an instance of severe suffering… Therefore, it justifies redistribution*, with each of the categories involved being crisp ones. (I am omitting some obvious qualifications here, to keep the example simple.)

Clearly, I cannot do this. I would have to rely on evidence from my observation of the visible behaviour of others, my inferences about which of their reactions are 'normal', and introspection; but all of this evidence is necessarily fuzzy, and therefore inadmissible in conventional logic. (I cannot, for example, be certain – in the CL sense of deductive truth – that I am not comparing someone who has a pathological addiction to caviar with a psychotically unfeeling parent, nor can I exclude such cases by creating a non-crisp category of 'normal' individuals.) None of this is a problem in fuzzy logic, where categories that are not crisp and do overlap are valid, and where any claim I make about my ability to compare extreme levels of pleasure and pain in others, or to classify the reactions of individuals as 'normal' or otherwise, is an empirical matter. In CL, *form* determines truth; in FL, *content* determines truth; and a little reflection will confirm that virtually nothing in the physical and social worlds can meet the requirements of CL – which, of course, is why we do not use it in everyday life.

4.2 Genetic Algorithms.

Finding out what rules intelligent, non-altruistic suppliers would adopt to survive and prosper in a complex marketplace requires some means of optimising complex objects, *viz*, the fuzzy rulesets. A genetic algorithm (GA) does this by mimicking the process of organic evolution[11], in which the selection of novel characteristics leads to improved adaptation. (The method rests on an analogy between strings of digits encoding a potential solution to a problem of interest, and chromosomes, which embody strings of genetic code.) Mutation is the best known of the novelty-producing mechanisms, but crossover – the process in which parental chromosomes are aligned, severed at corresponding points, and then re-connected in such a way that the offspring chromosomes receive a mixture of parental genes – is at least as important [20]. (The effects of evolution in natural, 'wet' genetics are vastly more complex than in this one-gene-one-function version [21]; and biological evolution does not appear to be in the business of optimisation.) The algorithm consists of these steps:

- create a population of strings, each encoding one possible (random) solution to the problem at hand (e.g., a set of rules for responding to changing external conditions);
- implant each of these solutions in an agent;
- see which strings are fittest, by noting which agents perform best (in this context, the natural choice for a measure of fitness is the ability to make sustained profit);
- put the best of these strings into a simulated breeding programme, ensuring that the fittest strings contribute more 'offspring' to the next generation;
- implant these offspring in new agents, and repeat the two previous steps until some halting criterion is met (e.g., until profitability ceases to increase with successive generations).

Under certain conditions (see below), the population of strings will converge onto a single, learned, optimal form. In this case, predefined membership functions were used for the input membership functions, and a standard profile was used for the

[11] Readers who have religious scruples about evolution should regard this as a case of a myth that has, in this case, produced a serendipitous effect.

output membership functions (OMFs), so that only fifteen decimal numbers had to be optimised (one for the central keypoint of each rule's OMF).

5. Findings.

(i) In a separate trial, firms had been able to learn the asking price as a single number, rather than a set of fuzzy rules; however, under complex dynamics, this produced much lower levels of profit. Intelligent, self-regarding agents would therefore choose a strategy of dynamic, rule-based responses.

(ii) Under simple dynamics, regardless of the level of risk, firms learnt, convergently, sets of rules whose effect was to drive the market price to the static equilibrium level[12]. As long as the conditions for perfect competition – or a near approximation to them – are met, the FL/ GA combination produces, experimentally, the same result as the reasoning used in constructing the standard model of competitive markets.

(iii) Under complex dynamics, firms also learnt a set of rules that took them to equilibrium. This is somewhat surprising: nonlinear systems often have restless – even chaotic – dynamics. (The significantly different feature here is the presence of intelligent agents, of course.) However, the equilibrium price was different from the classic one, by an amount that depended on the level of risk; the percentage depression at each level was consistent across markets, with a 10% difference at the highest level.

(iv) The standard arguments for the optimality of static competitive market equilibria in simple economic systems cannot apply in the corresponding dynamic equilibria in complex ones.

(v) These equilibria were also qualitatively different from the classic ones. In the standard model, it is assumed that firms have already pushed their production up to the level at which price and marginal cost are equal, thus maximizing profits. Here, they learnt to aim below the classic (static) equilibrium price to avoid bankruptcy. Even the simple best-of-three-bids process efficiently allocated demand preferentially to the cheapest vendors; but when the risk-generator built into the model drove

[12] The correlation between the actual price at the end of a simulation and the corresponding theoretical (static) equilibrium price was over 0.99, across 10 markets, in which the actual equilibrium price varied by a factor of approximately 10.

demand down, this often left firms at the top of the price ranking with no sales. A very small difference in absolute price between two firms could mean that one has a large income, while the other has none, and therefore risks bankruptcy; a firm's ranking can also be changed by other firms adjusting their prices, of course. (The same pattern of rules results when consumers are not allowed to switch suppliers unless the price differential exceeds a certain minimum.)

(vi) Firms learnt to use rules that keep the market stable. This is a significant derogation from economic rationality (ER). Actors are ER[13] if they always choose options that promise the maximum net benefit to self, assessed on the economic value current transaction only, i.e., they are materialist, non-altruistic and chronomyopic[14]. While ER is still the winning strategy for non-altruistic agents in simple market systems (see (ii), above), this is not true in complex settings, where the vigorous pursuit of individual short-term advantage may modify the dynamics of the situation, to the disadvantage of all.

(vii) Under all simple treatments, the ability of firms to learn was unaffected by the number of trading periods between successive passes of the GA. However, under complex dynamics, learning broke down completely with less than 4 trading periods between GAs. It appears that, in the complex case, the consequences of any particular strategy are more variable, and can only be evaluated adequately in a longer sample.

6. The Potential of Genetic Algorithms.

In the 1990s, there was great optimism about the potential of GAs, and many simple applications were published [22]. This initial optimism was soon replaced by an equally mistaken pessimism, when it was realized that, as problems get bigger, the number of generations and the population size required to solve them grows very rapidly, and eventually, this makes the method impracticable. It is possible to adopt more sophisticated genetic methodology, such as messy genetic algorithms (MGA), in

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[13] For the sake of brevity, 'ER' is used for the noun, adjective, and adverb.

[14] Myopic *tout court* would be as accurate, as the short-sightedness does not apply solely to time, of course; and it is only possible to be ER if the expected outcomes of choices are predictable, which is not true of many complex situations.

which the coding structure of the strings – in particular, their length and how the variables are grouped together – is also allowed to evolve [23]. (There is still debate about what mechanism is responsible for the efficiency of GAs in general [24].)

However, it is also possible to simplify the genetic structure of a given problem. GA-based methods can be computationally demanding in two different ways. Increasing the number of steps in the technical processes involved (such as setting an asking price, adjusting plant capacity, calculating profit and cashflow, etc), results only in a proportionate increase in the computational burden. However, an increase in the *genetic* size and complexity of the problem is more serious, because it leads to an increase in the computational burden that grows much faster than the size of the problem (measured, in this case, by the number of independent decimal numbers that has to be learnt).

When the investigation was begun, an attempt was made to optimise all three keypoints of both input and output MFs, i.e., nine numbers per rule, for each of fifteen rules[15], making 135 in total. This failed consistently, the strings converging onto random formats, because of genetic drift; the root cause of this is *epistasis* [25], in which the quality of a solution is affected by the values at relatively widely-spaced loci. The nine numbers for each rule are spread out in sequence along the string, and the sever-and-interchange involved in crossover can therefore readily disrupt them; as a result, a segment of a good solution that has been assembled by mutation and crossover is likely to be promptly lost again. However, the tactic of using fixed input membership functions and a standard profile for the output membership functions meant that only a relatively short string of fifteen real numbers had to be learnt; and, because the overall response from a fuzzy ruleset is a weighted linear combination of the responses of individual rules, these numbers can be learned independently, precluding the possibility of epistasis – single numbers are not vulnerable to disruption by crossover.

GAs appear to be able to handle optimisation problems in which the agents belong to different groups (each heterogeneous) with conflicting interests [26]; and

[15] Five levels of profit, crossed with three levels of inventory, see above in main text.

techniques to allow different strategies to evolve within a single population have been available for many years [27].

7. Other Impacts of Complexity on Mainstream Economics.

7.1 Genetic Methods and Motivation, Altruism, and Professionalism in the Public Sector.

The account so far has focussed on part – a very significant part – of the core of MSE; it is now time to turn to the latter's halo of theories about motivation and institutions. A number of studies have been made of this, using various genetic methodologies, mostly in the last two decades. These studies create very serious doubts about economic rationality as a model of human motivation, the deficiencies being so great that ER cannot be treated as a reasonable approximation to the real world. (This is relevant to understanding the behaviour of economic agents in general, and actors in politics and the public sector in particular.)

The empirical support for the ER model was never a strong one; and it displaced an earlier series of models with a much stronger empirical base, which recognized and explained a wider range of phenomena. In those models, motivation is multi-dimensional (rather than solely a response to individual, short-term material reward) [28]; organizations are inherently prone to conflicts of goals and values (rather than single-minded 'rational actors', obeying a charter set by their owners/ sponsors) [29]; and most management and policy decisions are not well-structured ones (see below). (These models were a reaction to the defects of earlier ones that were primarily concerned with command and control, in environments that were technically, psychologically, and culturally simple [30].) The change cannot be attributed to increased explanatory power; in part, it seems to have been a Kuhnian paradigm shift, but considerable political effort and surprisingly large amounts of money have also been spent on promoting the MSE worldview [31, 32]. (The latter may go some way to explaining the finding that, even in fairly unequal capitalist societies, there is a widespread belief that the existing distribution of wealth has some just/ fair basis [33].)

In our context, it is the notion that people are *exclusively* selfish (as distinct from operating with mixed motives) that is most significant; if this is true, no form of altruism can be expected in politicians or public servants – no professional ethics, no idealism, no tincture of commitment to the public good in the intentions of politicians and their appointees. These ideas take their purest form in public choice theory (PCT). This takes it as axiomatic that politicians will confect policies solely to sell them to the public for votes, thereby to secure both the legitimate and corrupt benefits of public office, so that the overall direction of public sector policy is inevitably distorted.

This supposed effect is separate from the decrease in efficiency that is claimed to result from the absence of profit-driven owners – or their agents – in the public sector. (Orchard and Stretton offer an interesting critique of both sets of ideas, see [34].) The latter belief does pose problems of internal consistency: a number of financial debacles (including the current 'credit crunch') have had their roots in competitive pressure *within* firms, leading to actions by individuals that are far from being in the firm's long-term interest (see also [35]). It is difficult to see why a dichotomy between what the organization needs and what motivates individuals should lead to inefficiency in one setting (public sector), but not in another (private sector), given that the same range of management tools is available to both.

PCT and related approaches are based on two beliefs: that economic rationality is necessarily a winning strategy for non-altruistic agents; and that humans will be conditioned by Darwinian forces to be economically rational. We have already seen that the first is wrong, because ER action can set off turbulence that imposes costs on all, in a situation in which free-riding on communal self-restraint is impossible[16]. This is consistent with earlier work by Axelrod [36] on the Prisoners' Dilemma game (PD), in which two felons have individual incentives to betray the other to the authorities. These incentives (given certain conditions) drive them into a very damaging mutual betrayal, despite the existence of a much better collaborative solution, benefiting both equally, of supporting each other – a 'paradox of rationality'.

[16] Any firm that seeks to exploit the communal self-restraint can only do so by putting itself at the top of the ranking by asking price – but that is the place of maximum danger.

PD is a much simpler system than the complex markets considered above, and it imposes extreme simplifying conditions: blind play[17]; sequences of games of fixed length; and no tentative moves, signalling, or knowledge of the other's normal behaviour gained through other transactions. The surprising thing is not that PD produces defection from coalitions that would be mutually rewarding; it is how small a relaxation of those conditions is required to restore sanity (and collaboration) – in Axelrod's case, only the fixed-length sequences are done away with, and this led to the emergence of the famous Tit-for-Tat Strategy[18]. (In Brams' *Theory of Moves* [37], it is relaxation of the blind play rule that disrupts the 'paradox of rationality'.) Casti [38] and Axelrod [39] describe later work with GAs, which produces a richer variety of behaviour: selfish agents will learn to play PD in a way that does not trigger persistent, mutually destructive retaliation; and, although they may still attempt minor exploitative sequences of moves, mostly they have to act with restraint towards others, for fear of the reactions that would otherwise result. In these solutions, agents collaborate, but often, they do so grudgingly; they trust, but only provisionally; and they exploit, but with restraint. Like most of us, they display a mixture of selfishness and altruism.

More recent work in theoretical biology is equally damaging to the pseudo-Darwinian argument for *Homo economicus*. This work shows that biological evolution has repeatedly led to the development of altruism [40, 41]. (In biology, this term refers to a sacrifice of fitness by one individual, to benefit one or more others. Mainstream economists often seem to imply that 'true' altruism requires a disinterested *intention* to self-sacrifice in order to benefit others; and they attempt to explain away the whole phenomenon by showing that an alternative selfish explanation exists, the 'warm glow' that the altruist supposedly derives from his/ her actions. I am not aware of any attempt to confirm that this effect actually exists, or to explain how Darwinian forces would produce individuals who valued it, in the absence of a heritable functional benefit arising from altruistic behaviour.)

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[17] Players make their moves knowing the other's repertoire, but not which tactic will be used in any one interaction.

[18] Trust the other in the first exchange, then, in subsequent interactions, repay collaboration with collaboration, defection with defection.

In many cases, altruism acts through empathy. In the opening passages of *The Theory of Moral Sentiments*, Adam Smith attributes empathy solely to our ability to imagine ourselves undergoing another's tribulations, but this understates the phenomenon's strength. As we have seen, the inhabitants of any complex system experience strong evolutionary pressures in favour of mutually accommodative behaviour, and the results of this – a degree of functional empathy – have been confirmed experimentally in a number of species [42]. The result of this pressure is that empathetic features are now built into our neurophysiology; for a non-specialist account of the mechanisms involved, see [43]. We do actually share, to a greater or lesser extent, the brain phenomena that accompany pleasure, excitement, and distress in others, and therefore, presumably, we also share the same mental phenomena. The idea that there is no 'logical' basis for interpersonal comparability is not only wrong about the logic of the situation (see Box 1): it also depends upon an inaccurate model of mental functioning.

One principle links all these cases: ultra-simple situations favour models whose agents are ER; but even a small infusion of complexity – or, equally, any relaxation of the artificial simplifications – favours more restrained, collaborative strategies. In the purely biological cases, the damaging over-simplification appears to have been the assumption that individuals always form part of a single population, rather than belonging to groups that benefit from altruistic behaviour, but which periodically break up and re-form with different members. In the other cases, it was the exclusion of any repercussions of individual agents' actions that artificially favoured ER.

7.2 The Impact of Complexity on Theories of International Trade and Development.

In the light of Sections 5 and 6, it seems reasonable to think that the combination of FL/ GA with simulation experiments should be capable of handling complex models in other areas of economic theory, particularly in the areas of trade and development. However, there are four distinct groups of difficulties with the widely-held idea that freeing-up markets, domestically and internationally, will automatically improve the lot of the world's poor, and the availability of GA/ FL does not affect them equally.

(i) Internal criticisms. As in the case of competitive markets, there are problems of internal consistency in the MSE account of the benefits of *laissez-faire* in international trade; Graham Dunkley has provided a good survey of these [44]. The most serious of them concern the size and form of the benefits; the interested (or sceptical) reader should consult Dunkley's book. The ability to handle more realistic, complex models is likely to make these criticisms redundant.

(ii) Dynamic weaknesses. More fundamentally, mainstream theories of international trade and development inherit the weaknesses of competitive market theory. The static equilibria on which both are based are simply assumed to exist, and they may not be reachable in a dynamic situation. Indeed, this must be the case: mainstream theorists typically assume that the economies involved will all be operating at the limit of their current productive capacity, i.e., they have been pushed, by competitive forces, to their respective production possibility frontiers (PPFs), with all their constituent markets at the classic, static equilibrium. However, we have already seen that it is not in the interests of the firms in individual markets to behave in ways that lead to that state.

GA/ FL does appear capable of building more realistic theory in this area (although doing so would obviously constitute a major research programme). The methodology may also be capable of illuminating the recurrent issue of how policy-makers should respond to challenges, given that they are in a world of very imperfect markets – and, indeed, may be on a very unlevel playing field, if, for example, their country's primary exports may have to compete internationally with the subsidized output of richer countries. (A substantial part of the current[19] difficulties of the Doha trade negotiations has arisen through more prosperous nations attempting to continue to protect their own agricultural producers, while asking poorer ones to liberalize in other sectors [45].) In effect, this involves exploring which second-best options are likely to be no worse than *second*-best. However, this issue is also very close to an important boundary, see Section 8, below.

[19] August 2008.

(iii) Origin of markets. The problem of purely economic development will not be solved by the spontaneous appearance of markets in which producers make (or retail from existing sources) products for direct sale to consumers, in response to demand. Recent experience in Liberia illustrates this. In the aftermath of the civil war, petty trading in crockery, soap, tobacco, etc did pick up spontaneously in response to consumer demand. However, sectors in which sales for final consumption depended on the renewal of a chain of economic activities did not. In the case of marine fisheries, for example, there is a good demand inland, and the various means of satisfying it appear to be potentially profitable. However, by the end of 2006, very few fish were being sold outside Monrovia, and those were only being sold, on a small-scale, by hawkers.

GB Richardson identified two factors that account for this kind of tardiness [46]. Entrepreneurs may be reluctant to respond to new market opportunities, if they suspect that others are making similar, competitive investments that will lead to an excess of total capacity. They will also be reluctant, if there is uncertainty about whether others are making the complementary investments on which they must rely for inputs, services, etc (in the Liberian example, ice producers, canners and/ or smokers, suppliers of packaging, refrigerated transport and storage, etc). When investment does happen in such circumstances, it is almost inevitably followed by a costly shakeout of excess capacity. Developing economies cannot afford this; and it is nonsense (or worse) to suggest that there are sound theoretical or empirical grounds for believing that allowing either of the main possibilities (inaction or shakeout) to happen, is optimal, or even simply better than the modest state action of the kind Richardson suggests: the case simply has not been examined.

He should perhaps have added that the factors that actually determine where entrepreneurs put their money are usually not dominated by expected return on investment; this is largely for valid reasons concerned with rational decision-making in environments that are not merely risky, but uncertain (see below). And, of course, even if those decisions were dominated by the expected rate of return, entrepreneurs would be comparing alternatives across many sectors, and would not necessarily choose to invest in all the activities that a prudent, long-sighted, and humane government would favour.

(iv) Income Distribution. 'Development' implies change in the quality of life throughout society, and it is difficult to see how this can happen, without some considerable improvement of the material circumstances of the poor. The 'trickle down effect' can hardly be relied on to help them, even in the medium term [47]: it is considerably easier to raise GDP than to raise the relative incomes of those whose earnings lie in the bottom quintile, by relying on market forces and liberalization. It is difficult to see how any effective poverty alleviation strategy can avoid creating both gainers and losers, and the latter – including those who misperceive themselves as long-term net losers – may well resist the changes, through political and other means.

Poverty is primarily a matter of distribution, in two senses. Firstly, there is the immediate inability of the poorest to buy food or health care, or to invest in education, because of the absolute level of their income. Secondly, markets and the private sector – unless regulated or persuaded by incentives – inevitably go where the money is, evolving over time to meet, preferentially, the needs of the richer sectors of society, i.e., there is also a problem of relative incomes. Now, there are aspects of distribution, *as a purely economic problem*, that are complex in the sense used here, and which appear to be amenable to methodology such as GA/ FL (for example, its dual nature, both an input to, and a consequence of, economic arrangements). However, there are other aspects that are political, and these lie beyond the boundary between that which can usefully be explored by economic model- and theory-building, and that which cannot.

8. The Limits to Theorization and Model-building.

8.1. Problem Structure and the Concept of Rational Decision.

Simple and complex situations correspond to Mitroff's well-structured and ill-structured domains, respectively [48]. In the former case, effective conduct lies in finding the best option, and implementing that; and, accordingly, methods for making a selection from a *given* list of options form an important part of the decision-maker's toolkit in this context.

However, in ill-structured situations, because of uncertainty and ambiguity, the nature of any problem, how to solve it, and what counts as a good solution are all open to dispute. In this domain, our effectiveness depends to a large extent on our skill in framing the problem at hand in a potent way, in applying techniques for creatively expanding the range of possible solutions open to us – and in managing our choice well, for here, the likelihood of unforeseeable consequences arising from our actions is always relatively high. But there are also hyper-complex situations, in which political conflict is an added ingredient, i.e., there is conflict about which paradigm and set of values should determine the allocation of rights, duties, and benefits in a society. These correspond to Mitroff's wickedly-structured domain, where building coalitions, neutralizing opponents, gaining control of resources, gaining control of critical posts and functions, moving disputes into more congenial forums, and moulding public opinion, are fundamental to effectiveness[20].

Both Keynes and Knight (see [5]) believed that people respond to genuine uncertainty (as distinct from mere, quantifiable risk) with some form of irrational behaviour. This is an error, and it arises from the assumption that 'rationality' can only mean 'economic rationality' (in the sense explicated above). Given the richer understanding of rationality that grows out of the concept of problem structure, it is easier to see how rational decisions can still be made in circumstances in which the conditions and inputs required for ER simply do not exist; and the basis on which actors make reasoned choices in such situations may well be quite different from what they would rely on in the corresponding well-structured ones. For example, when an

[20] The most one can reasonably expect to achieve consistently is, of course, different in the three domains: achievement of short-range goals, attaining broad objectives, and furtherance of one's fundamental values, respectively.

entrepreneur has to make an *ill-structured* choice among potential investments, factors other than the prospective return on investment – which may be very uncertain – may dominate his/ her choice[21].

The author had some years' experience with one of the UK Enterprise Agencies, working with the owners of small firms that were trying to diversify their portfolios of products. There, provided that the prospective return was judged to be broadly satisfactory, the final decision about a new product was usually determined by considerations of prospects for growth, the possibility of dominating a niche market, or what would be easiest to manage if technical or marketing problems arose, rather than any fine comparison of expected returns. All the factors mentioned are, of course, partial determinants of the actual, realized returns; but all are also uncertain, and cannot generally be quantified in any meaningful way – rather, they provide a strategic base from which to confront unexpected threats and opportunities in the future. Similar considerations apply in the context of R&D, where most significant choices are ill-structured or wickedly-structured; for a discussion of the principles of decision-making in the latter situation, see [49].

8.2 The Role and Limitations of Rational Decision in Development.

Two rather different situations illustrate the issues involved. One is the persistent problem of attempting to stimulate economic development (accepting that development has other, important dimensions that nevertheless depend on increased economic activity). The other is the type of problem currently facing some rice-exporting countries during a period of sharply increasing prices. If rice is both an important export and a staple item of diet, then export tariffs and restrictions will have many interconnected consequences of a purely economic nature. They will also affect different sectors of society (e.g., urban wage-earners and farmers) differently; and any political tensions that arise may affect government's willingness and even its ability (in the face of widespread unrest, for example) to pursue its chosen policies.

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[21] Note also that, in such cases, you cannot work back from the choice to determine what rate of return the entrepreneur 'really' expected: the data/ choice relationship is neither one-to-one nor invertible.

In both these cases, more sophisticated methodology – to build basic theory, or to explore the technical aspects of the behaviour of complex economic systems – has an important role to play in informing political decisions. However, I suggest that the actual decision will, in virtually every case, have to be situation-specific, and involve compromises among desirable but mutually incompatible elements. In particular, the 'best' choice will depend on the skills and the relative strength of the political assets of the decision-takers. This view conflicts with parts of the 'Washington Consensus' [50] – which is still believed in, fervently, by many of the staff of development finance agencies – that such choices are always objective ones, and there are always over-riding arguments in favour of maximizing market freedom.

The technical weaknesses of the underpinnings of that consensus have already been outlined, but a sense that there is a strong *philosophical* case for market freedom persists. This opens up the vast field of ethics, and all that can be done here is to put forward some comments on the sturdiest arguments of two of the best-known advocates of this position, Friedrich Hayek and Robert Nozick.

(i) Friedrich Hayek remains an important influence[22]. He argues that coercion is unavoidable in a planned society – as the only way of getting compliance with the plans – and that this will lead to a climate in which the ruthless self-seeker is likely to flourish, and will inevitably end in dictatorship, since this provides the most effective means of coercion [52]. His use of the phrase 'planned society' assumes that a very substantial amount of centralization has already occurred: most mixed economies operate on negotiation, of one form or another. He has really only succeeded in showing that a process of moral degeneration and increasing centralization of control is likely where bureaucrats already have very wide-ranging powers and responsibilities, and operate in a system that provides no countervailing force to resist their supposedly relentless search for power – and that they actually desire power in the first place. (Some bureaucracies go the other way, of course, seeking an easy life for their members by *shedding* responsibilities; see [53] for examples.) Hayek also fatally weakens his position by offering an explanation of why freedom is good: if the

[22] He was awarded the US Presidential Medal of Freedom in 1991, a year before his death. More recently, Jeremy Shearmur's *Hayek and After* [51] gives a good critique of Hayek's work, and also testifies to the continuing strength of his influence.

justification for rejecting 'coercion' is freedom, and his justification for wanting freedom is a particular quality of life – in which individuals are able to use their mental powers to the full, and thereby make their full contribution to the community – then it is the latter that really matters. If there is some other way of attaining that quality of life, one that does not depend on freedom in his sense, then, surely, he should be prepared to consider it.

(ii) Robert Nozick put forward a number of arguments for minimalizing the role of the state. Central to these is his claim that there can never be *any* moral justification for 'aggression', which he defines as including any taxation beyond that required for the minimal, night-watchman state (introducing an element of circularity into his argument in the process). He justifies this absolute ban by citing Kant's categorical imperative, never to treat humanity simply as a means, but always to recognize that they are in themselves, 'an end' (i.e., they are rational, moral agents) [54].

However, using the categorical imperative in this way radically distorts its author's intention. Kant believed that moral force derives from reason. We have moral precepts, such as 'do not cheat'; these can be applied universally; and they are binding, because they admit no *meaningful* alternative. If you try to invert such a precept – so that you might get 'always cheat', for example – the result is self-destructive: in this case, if the inverted version were applied universally, the very concept of honest dealing would break down, and it would no longer be possible even to define the meaning of 'cheating'[23]. According to Kant, our reason tells us what is right – but it is our will that makes us actually do what is right, when we act 'autonomously', with reason and will in harmony [55, 56]. *Good* will, therefore, has a very special status, and should be inviolate; but Kant acknowledges that we also act 'heteronomously', e.g., in pursuit of physical pleasure, and it is entirely clear that he did not intend to extend this special status to that sort of situation. Whether one accepts his arguments is irrelevant: even if they are correct, Nozick is misusing Kant's conclusions.

[23] Kant has a different – and much looser – argument for precepts on which this one does not work, such as 'do not neglect your talents'.

9. Conclusion.

9.1 The Current Status of Mainstream Economic Theory.

The findings reported above on the behaviour of firms in complex competitive markets (like all experimental results) need confirmation. If they stand, and the contention that the 'complex' treatments are a better approximation to reality than the model of perfect competition is accepted, then certain other results must fall. Firstly, competition among materialist, non-altruistic (but non-myopic) agents will not bring single-commodity markets to the classic, static equilibria, so that the standard arguments for the allocative efficiency of competitive markets do not apply; and the same is true of the standard arguments for believing that competition ensures that each factor of production receives its just reward, and that no one agent can have any incentive to 'exploit' another.

Furthermore, mainstream theories of international trade rely heavily on the assumption that economies operate at the production possibility frontier; but given the results reported in Section 5 on the behaviour of firms in individual markets, it is very difficult to see how this could be the case. If it is not, doubts are cast on the usefulness of those theories as sources of policy guidance, and on claims that *indiscriminate* market liberalization is the key to improving the lot of the world's poorest people.

These considerations remove both the material and moral bases of thinking that unfettered competition should be the default choice for economic arrangements (and the philosophical case for libertarianism, as expressed by Hayek and by Nozick, is not a strong one). They also leave us with the problem of managing mixed economies. While there is a vast amount of practical experience on this (not all with impressive results, and some of it difficult to explain), we do not yet have a solid body of realistic theory in this area. Such theory should be able to guide us in identifying when intervention is advisable – because intervention has both direct and indirect costs, and these can be heavy – and in identifying the type and intensity of intervention needed. Producing such theory would be a very substantial exercise, and one that could reasonably be regarded as the acid test of any school of ideas that claims to offer a radically better way of ‘doing economics’. It is in the highest degree unlikely that any such body of theory would displace market forces from centre stage; but it is increasingly difficult to present a convincing case for leaving them completely unmanaged (and, indeed, no modern state actually does so). However, a managed, mixed economy would also require a more balanced approach to the relative roles of the public and private sectors, supported by renewed efforts to understand organizations and institutions as complex systems, whose inhabitants have a variety of motivations (see Section 7.1).

From the evidence presented above, it does seem that many of the characteristic features of MSE (in the broad, two-component sense used here) are artefacts of simplifications that were originally made in the interests of mathematical tractability. These features include: the supposed stability and other benign properties of perfectly competitive markets; the existence of paradoxes of rationality; and the inherent superiority of the private sector over the public sector. At the very least, this evidence shows that there is an alternative perspective that is worth exploring; some of the avenues for such exploration (and the robustness of the available navigation instruments) have already been discussed in the main text.

9.2 The Prospects for Change.

This is the appropriate point to clarify the word ‘perspectives’ used in the title, particularly in relation to ‘paradigms’. The work of Thomas Kuhn, Imre Lakatos, and Larry Laudan in this area can, I believe, be synthesized as follows. There are, indeed, opaque Kuhnian paradigms. These are visions of the ‘true nature’ of reality, shared by members of a discipline, that are so compelling that any theoretical or empirical evidence suggesting that they are mirages is rejected (by various means), in order to justify continued belief in the vision [57]. The mental imagery of humans as member of the genus *H. economicus*, is – among one set of economists – an example of a paradigm.

Anyone who challenges such a vision of reality is putting forward something rather more in the nature of a Lakatian research programme [58]: a vision of a sequence of problems, placed in the order in which they need to be addressed. Lakatian research programmes are also exist in the real world; most (sub-) disciplines are demarcated by a paradigm – which their members take as a direct view of the very bedrock of reality – and one or more research programmes, all of which their members share. The difference between a paradigm and one of these programmes is that Lakatos did not share Kuhn's belief in the impossibility of individual investigators escaping from their discipline's shared, communal vision of the true nature of its subject matter: Lakatian research programmes (RPs) are adopted, consciously and voluntarily, by the individual researcher[24], who may switch back and forth between them. He also drew attention to the two types of criteria that working scientists use in making that choice: those they apply to established RPs (solidity and significance of actual achievements), and those they apply to new RPs (promise of solving intransigent anomalies).

Laudan made two further significant contributions to the debate [59]. Firstly, he pointed out that anomalies may be tolerated, if they persist long enough, and if there is no alternative that is capable of doing all that the incumbent theory can do, *and handling the anomaly as well*. Secondly, he presented cases in which a dominant paradigm – and its image of reality – simply faded away, when changes in the wider intellectual culture (in which science is always embedded) eroded the credibility of that image.

In effect, the alternative presented here is a research programme of Lakatos' second sort, i.e., one that is consciously advocated for its promise of dealing with anomalies and defects. The advocates of such a programme are usually aware of the hidden assumptions about 'how the world really is' that support whatever they are trying to replace; but, inevitably, they too have their own paradigmatic blind spots. The future of this particular research programme may well be affected positively by both of the mechanisms discussed by Laudan, despite the massive, continuing expenditure on promoting the mainstream perspective as true, and, indeed, the only honest and reasonable view of political economy (see Note [32]). Firstly, it offers good prospects of handling the present subject matter of economics, while also

[24] He did acknowledge that RPs could still contain mechanisms – 'negative heuristics' – that neutralize evidence against their own core assumptions.

dealing with the important issues that centre on the simple/ complex dichotomy. Secondly, the credibility of what it seeks to replace – MSE – is likely to be undermined by the increasing dissonance between the simple systems view on which MSE is based, and the growing awareness of the complexity of natural and socio-economic systems that now forms part of the wider Western culture[25].

However, forecasting in any greater detail the future influence of this new perspective (and any achievements it may give rise to) requires methodology that would enable us to 'look into the seeds of time, and say which grain will grow, and which will not'. This we do not yet seem to have – not for complex systems, at any rate.

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[25] Most people, for example, have some idea of what 'the butterfly effect' refers to, and are awre of the concept of 'tipping points' in both the social and natural realms.

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