Organization, Anticipation, and Closure in Markets and Science

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Abstract: The approach of some systems biologists, Robert Rosen in particular, to the understanding of biological systems calls for a focus on the organization of the processes internal to such systems, rather than on equilibrium states characterized in material terms and their state transitions viewed as taking place according to dynamical laws. A similar approach is possible for social systems. It is shown that the basic processes operative in both markets and science can be understood as being organized such that these systems exhibit material openness, process closure in the sense of a complete causal cycle, and anticipation based on the maintenance of an internal model of the system's environment.

Keywords: markets, science, organization, anticipatory systems, process closure.

I. INTRODUCTION

I present here a new approach to the understanding of market (and other) systems of social interaction. Although, perhaps inevitably, I appear critical of existing methods, specifically by economists, for modeling such systems, it is not my intention to represent this new approach as the royal road toward understanding—social systems are complex arrangements, and as such they admit of many perspectives that can be useful in their investigation. What is 'new' about this approach, and why it can be complementary to other approaches, is that it is based on the idea that the organization of the processes active within a social system, their dependencies and how they interact, is at least as deserving of attention as are the states of the system characterized in terms of the actors and the material components. For the initial elaboration of that idea, I set the context as the market economy.

Macroeconomics, the study of the economy as a whole, has developed over many years from the general equilibrium equations of Walras through the marriage with some of Keynes's ideas in the neoclassical synthesis, to the modern dynamic stochastic general equilibrium models which are thought to model the economy, or at least large parts of it, sufficiently well to provide useful guidance to central bankers and other policymakers. Walras self-consciously took his system of equations from classical mechanics, which, not unexpectedly, raised questions of applicability to systems of human interaction, but, in the long process of assimilation and development of Walras's system, where mathematical consistency conflicted with realism of assumptions, it was the former that won out.[1] In particular, the problem of interactions between agents has been avoided by the device of the representative agent, and the problem of agent expectations has been sidestepped by the assumption that the single agent's expectations are never systematically different from the equilibrium of the model.[2] The modern models may be significantly more sophisticated than Walras's original, but they have in common with it that they represent the market economy as a mathematical machine.

The purpose of these models is to compute snapshots of equilibrium states of the economy (in terms of aggregate quantities such as GDP, unemployment level, and inflation rate) resulting from given initial conditions, and this focus on end states does not, and is not intended to, provide understanding of the ways in which the interactions between the individual participants in the economy might (or might not) move the system as a whole toward an equilibrium state. So, criticism for lack of realism in this regard rather begs the question. But the lack of consideration of the processes of interaction, of the constraints faced by the interacting parties, and of the fact that disequilibrium, rather than equilibrium, would appear to be the more realistic characterization of the normal state of affairs in a market economy, has left a gap. Market process economics, which covers a diverse range of inquiry ranging from evolutionary economics to the theory of the entrepreneur (both Schumpeterian and Austrian) is a recognition of the need to fill this gap, but although much useful work has been done in understanding difficult phenomena such as expectations, entrepreneurship, learning, confidence, and the consequences of regime uncertainty, little or none of this can be readily integrated into the mainstream models.[3]

By focusing on processes of interpersonal interaction and the constraints, incentives, and possibilities for knowledge transmission that they embody, rather than on equilibrium end states, the various strands of market process theories are able to provide understanding of economic activity involved in internal state transitions and of the constraints which impinge on this activity and which are in turn moulded by it. But they do not add up to a theory of the economy as a whole. While we learn a great deal about the nature and operation of particular economic processes, we learn very little as to how these processes are organized, how they are interlinked, how they depend on each other, and how they work together to produce and maintain the complex system that is the economy. The obvious suggestion that follows is that it would be helpful to have, as a complement to theories of process operation, a theory of process organization. That is the thrust of what follows: I describe, admittedly in very general terms, the interactions and co-dependencies of the most basic processes operative in a market economy. The exclusive concentration on organization means that normal economic data referring to the movements and magnitudes of quantities of goods, services, and money, and the prices of such things, play no part; it is the structure of the interplay of processes that is in focus.

A number of interesting results follow from a myopic concentration on process organization. First, it becomes plausible that the form of organization in a market economy is conducive to the adaptation of the system as a whole to its environment. Second, one of the organizational elements can be characterized as functioning as an internal model of the system's environment—that is to say, the system is not merely adaptive, but capable of a form of anticipation. Third, the system is a complete self-maintaining whole in the sense that, under the assumed constraints, the conditions for the operation of each of its processes are provided by at least one other process in the system. While the system is materially and energetically open, there is process closure in the limited sense that the processes form a causal cycle. Apart from the maintenance of some fundamental constraints, the system requires no outside process for ensuring that its operation can continue. Fourth, it seems likely that other systems of human interaction can be described in similar organizational terms, and I show as an example how the basic processes operative in the community of interacting scientists can be understood as also being organized into an adaptive, anticipatory system with process closure.

II. BACKGROUND

The basic idea that the organization of system processes is at least as important a subject of study as the physical effects of those processes has a long history in biology,[4] dating back at least to Kant but with earlier glimmerings as far back as Aristotle.[5] Kant (1790) described biological organisms as purposeful systems in which the parts 'so combine in the unity of a whole that they are reciprocally cause and effect of each other's form'. He pointed out that such systems are self-organizing and self-maintaining: the system is formed and maintained by the interaction of the parts of the system, and the parts are formed and maintained by the system's processes.[6] He contrasted such systems with a mechanical arrangement such as clockwork, in which 'one part is for the sake of the others, but it does not exist by their means. In this case the producing cause of the parts and of their form is not contained in the nature (of the material), but is external to it'. Machines require external maintenance processes; organisms do not.

Although Kant's characterization of biological organization was well appreciated throughout the 19th century, it was not until the 1920s that the idea of 'systems thinking' gained major traction in the work of biologists, particularly Bertalanffy (1928).[7] In arguing for biology's status as a science independent of physics, he directed attention to the emergence of phenomena at the system level, phenomena that arose only as a result of the interactions of the system components and were not reducible to the characteristics of the components in isolation. It is notable that when Bertalanffy talked about the organization of a biological system he emphasized the organization of the internal processes rather than the organization of the physical matter—in fact, he held that the former determined the latter. In Bertalanffy's (1968, p. 27) own words: 'In the last resort, structure (i.e., order of parts) and function (order of processes) may be the very same thing: in the physical world matter dissolves into a play of energies, and in the biological world structures are the expression of a flow of processes.' This prescient observation foreshadows recent developments in process metaphysics, which takes the fundamental nature of the world to be organizations of processes.[8] Bertalanffy also elaborated on the thermodynamic openness of such systems, describing organisms as systems in 'flux equilibrium', dynamically maintaining themselves through exchange of matter and energy with the environment.[9]

In the development of his theory of cognitive development in children as a self-organizing complex of processes, Piaget, working from an analogy with biological systems, introduced the concept of closure as the operation in the system of a set of processes which, together, without the aid of any outside process, reconstitute each other and thus maintain the operation of the system. Coupled with Bertalanffy's notion of thermodynamic openness, this conceptual combination characterizes biological systems as materially and energetically open systems with closed, self-maintaining organization.[10] The persistence in such systems is in the functional processes within the system; the physical components are continuously being reconstituted with the help of inputs from the environment.

Rosen (1985, 1991) made two significant contributions to the theory of biological systems: a general treatment of anticipation based on the many examples of anticipatory behaviour evident in biological systems, and a reformulation of the twin phenomena of thermodynamic openness and process closure in terms of the Aristotelian categories of causation.[11] These two contributions are closely linked, as will become evident. Rosen's treatments in both cases were highly mathematical—he did, after all, style himself as a 'mathematical biologist'[12]—but the essential ideas behind his work can be understood with a minimum of mathematical notation.

A process **f** which transforms inputs A to outputs B can be represented as **f**: A → B, i.e., as a mapping from domain A to range B. To give a specific example used by Rosen, **f** could represent a metabolic process in which food items (elements of the domain set A) were processed to produce items of fuel (elements of the range set B). It is possible for the domain and range set elements to be themselves mappings—for example, the mapping process **f**, realized as an enzyme, could itself be the product of a replacement process replenishing the metabolic enzyme from available inputs. Given the process notation **f**: A → B, Rosen (1991) identified the material cause of (the elements of) B as (the relevant elements of) A, and the efficient cause of B as **f**. Interacting combinations of such processes, represented in terms of such mappings, describe the organizational structure of the system as a whole. The thermodynamic openness of biological systems was, for Rosen, represented by openness to material causation, while process closure was represented by closure to efficient causation, i.e., a network of mappings which every mapping was an entity in the range set of at least one of its companion mappings within the network.

In addition to material openness and efficient closure, the capacity for adaptation is another characteristic of biological systems. As open systems, they are affected by environmental change, and may react to that change in various ways that maintain their structure and coherence, including the adoption of internal changes. Simple biological systems may adapt wholly as feedback homeostats that smooth out randomness in the environment, but in more complex systems there is the phenomenon of anticipation, where adaptation is informed by a prediction of possible future states of the environment. Rosen (1974) defined 'anticipatory modes of behaviour of organisms … [as those] in which an organism's present behaviour is determined by: (a) sensory information about the present state of the environment; and (b) an "internal model" of the world, which makes predictions about future states on the basis of the present data and the organism's possible reactions to it.' Note that this phenomenon of anticipation allows for a straightforward understanding of final cause as a possible future state which is anticipated in the present.

Rosen's work has been very influential among 'organicist' biologists, and while there is ongoing debate surrounding some of his more detailed claims, his status as a prominent contributor to the field seems assured.[13] The general attributes of thermodynamic openness, process closure, and anticipatory adaptation are all recognized as salient characteristics of biological organisms, although work continues to understand how the processes responsible for these characteristics function at a more specific level. But the biological details, however interesting, are not the concern here—what is of present interest is to what extent those characteristics of biological systems have analogues in social systems, and whether such analogies assist in understanding the function of social systems.

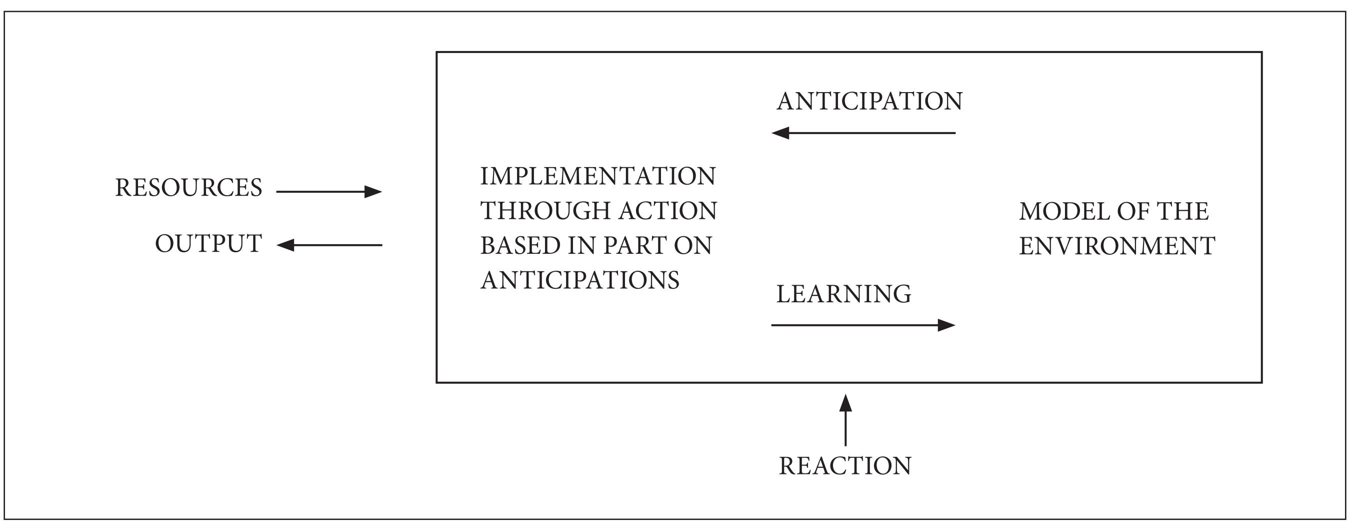
III. APPLICABILITY

The employment of biological analogies to economics and social theory has a long, interesting, and sometimes controversial history.[14] Even as careful an economist as Alfred Marshall was very inclined to countenance the future usefulness of biological analogies. In fact, he is widely quoted as saying (1920, p. 14) that 'the Mecca of the economist lies in economic biology rather than in economic dynamics'.[15] Less often quoted, however, is the warning that follows this directly: 'But biological conceptions are more complex than those of mechanics …'. And this complexity, though not incompatible with the subject matter, leaves a lot of room for misapplication. Rosen, on the other hand, was definite about the need to pursue biological analogies, specifically where adaptation was evident.[16] The social systems considered here, markets and science, have been characterized by numerous authors as 'complex adaptive systems',[17] and so the domain of applicability seems reasonable. What is of interest here, however, is the analogy, not simply to biological adaptiveness, but to biological anticipation in the context of thermodynamic openness and process closure.

The possibility for the application of these characteristics of biological systems to social contexts has not gone unnoticed. Rosen himself explicitly entertained the idea, discussing at length how understandings of adaptiveness in complex biological systems might be usefully applied to complex economic systems.[18] Leydesdorff & Dubois (2004) incorporate anticipation into a social system of interacting groups modeled by a version of the logistic equation. Louie & Poli (2011) discuss the application, at a very high level of generality, of Louie's extension of Rosen's work on self-referential systems to physiology, ecology, cognitive science, and social science, concluding that many natural systems, including brains and societies, appear to be systems closed to efficient causation. But while suggestive, none of these applications rises to a level much beyond the citing of possibilities and rather vague hints as to how progress might be made.

To summarize Rosen's picture of anticipatory systems, a system is anticipatory if it contains a predictive model of itself and of its environment which allows it to change state on account of the model's predictions as to a future situation. This ability to develop plans for possible futures, to form expectations of the future based on an internal model, allows for modification of the system's current state in the course of implementing these plans or predictions and may result in output to the environment conditioned by that modification. And the system's input from the environment may be processed within the system to confront, and perhaps modify, the model—for the model to be useful for anticipation, the system must be capable of learning, i.e., adjusting its model to reflect experience of reactions from the environment, especially in situations where prior expectations were not met.

These essential features, in terms of process organization, of a materially open anticipatory system are illustrated in the following diagram, where the box represents the conceptual separation of the system from its environment:[19]



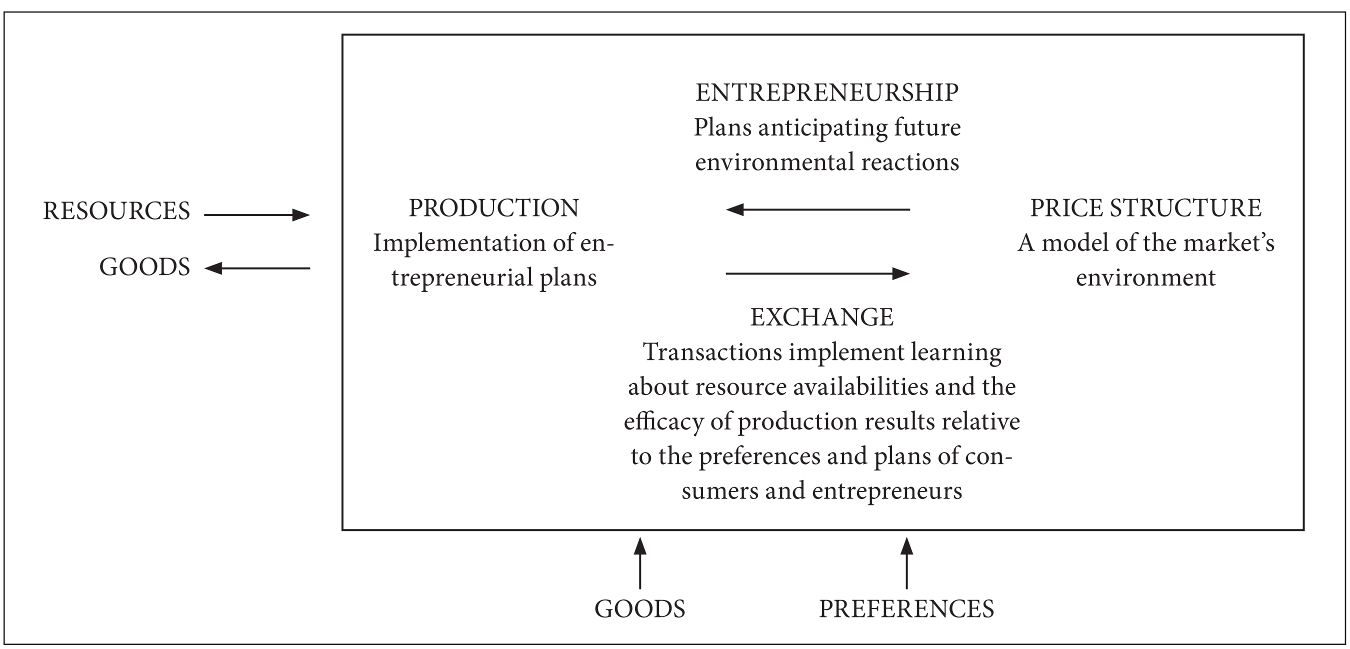
If this sort of arrangement is to have any relevance for understanding social systems, there must be identifiable, in the system of interest, a structure which serves as an actionable model of the system's environment, as well as processes which effectively update that model and which employ that model to influence the propensities of the system for interacting with the environment. The question of whether these processes constitute a closed set of processes can only be answered by a more specific characterization of the processes involved.

IV. MARKET PROCESSES

A 'market system', as defined here in very general terms, is a complex of people in their roles of producers, consumers, entrepreneurs, buyers, and sellers engaging in activity mediated by the institutions of property, contract, exchange, and money.[20] Observable as an emergent[21] result of the exchange interactions is the formation of a 'price structure'—most obviously, a set of generally recognized 'market prices' attached to specific goods and services, including capital goods,[22] each of which, while usually stable in the short run within small limits, can change as circumstances of supply and demand change. The sensitivity of the price structure to changes in external conditions and to changes in the preferences and plans of market participants makes it the obvious candidate for a structure within the system that serves as a model of the system's environment—a model that is continuously updated by environmental feedback transmitted by the agency of repeated exchange transactions.[23] Entrepreneurs within the system rely, at least in part, on price structure data in imagining plans for the production of future products and in assessing the feasibility of these projected production plans, and thus act as an anticipatory process affecting the system's production propensities.[24]

Exchange transactions in both consumer and capital goods are the instrument through which the system's model is continuously updated to register the state of external conditions relevant to the market system. The nature of the transactions is such that their effects are rarely so unstable as to be useless as information—in the case of prices, for example, attempted deviations from market price tend to encounter negative feedback in that, all other things being equal, a seller asking a price higher than the market price tends to lose business. But if all other things are not equal, if real circumstances of supply and demand change, then market prices do change in adaptation to the new environment. Similarly with the structure of capital goods—entrepreneurial success or failure, ultimately shown up in the course of exchange transactions reflecting consumer preferences, will result in changes not only to the prices of capital goods but also to their appraisals as complements and substitutes within the capital structure.[25]

Given these identifications of market process and structure, the overall process organization of the market system can be illustrated as follows:



It is to be emphasized that this is a high-level picture of the functional organization of a market system, not of the movement of physical things within the system. It can be contrasted with the old standard circular flow diagram, which depicts an economy solely in terms of the movements of materials—goods and money—and in so doing represents the economy as a purely mechanical system. But an economy (as being represented) is not a simple mechanical system—it is an anticipatory system whose states depend on possible future states. In incorporating and maintaining a working model of its environment, a model which can be accessed internally within the system to project the anticipated effects of future actions taken by the system, it implements creativity. Of course, the market system has components, the market participants, which are themselves creative, but it is not simply reducible to them, for it provides an organization within which these components can interact to combine creatively in ways that are not possible for them when acting independently.[26]

The specification given here of particular processes within the system uses, for convenience, the mapping notation of Rosen (1991) described above. The external 'material' elements (both tangible and intangible) impacting the market system are represented as the following sets (the memberships of which will change in the course of the system's operation):

- The set of resources R which enter the system from the environment.
- The set of subjective preferences S of market participants.
- Elements produced within the system are represented in terms of the following sets:
    - The price structure M which functions as an updatable model of the environment, as experienced by the system in terms of R and S.
    - The set of output goods and services O generated by the system's production processes.
    - The set of conjectures or plans C developed by entrepreneurs.

The processes[27] which constitute the dynamic elements of the system are as follows:

- **Exchange (x).** Out of repeated monetary exchanges of goods and services between market participants (acting according to their individual subjective preferences), each exchange transaction resulting in a price observable to other market participants, there emerges the price structure M, i.e., **x**: O, S → M.
- **Entrepreneurship (e).** This is a function of some market participants which, by projection based in part on the current price structure, generates plans or conjectures which act as dispositions to change elements of the system's productive activity, i.e., **e**: M → C.
- **Production (p)**: The implementation of entrepreneurial plans is a process that maps plans, resources, and (higher level) goods to (lower level) goods, i.e., **p**: C, R, O → O.

In summary, **x** uses O to produce M, **e** uses M to produce C, and **p** uses C to produce O, all with the aid of, and conditioned by, the external influences S and R.

It is the purposeful agency of the market participants, in the course of acting according to their subjective preferences and motivations ('pursuing happiness'), which provides the motive force animating the processes in the system. This is a major difference between biological systems and social systems—in social systems, the efficient causes all have as their basis the purposeful action of the participants in the system. There is not 'closure to efficient causation' in the same sense of the biological requirement for closure that the elements that act as efficient causes be generated within the system. The efficient closure in the market system, seen in the closed causal cycle of processes detailed above, is effected by the constraint that market participants pursue happiness in specific ways: they participate in exchange, entrepreneurship, and production under the institutions of property and contract—a set of processes which, given the system's material openness, are each necessary for the function of the others, and which together are sufficient to enable the system's existence as a self-maintaining entity.

The high-level picture of a market economy developed here is one of an epistemic system, a system capable of building within it some relevant knowledge of its environment, and capable of employing that knowledge to anticipate environmental effects and thereby to successfully adapt to them. Echoing Harper (1996, p. 282), it could usefully be described as a self-organizing and self-maintaining Popperian system[28] in that its adaptive apparatus consists of a process for developing conjectures based on existing knowledge, a process for implementing these conjectures so that they may be confronted by the environment, and a 'refutation' or 'error elimination' process through which failures and successes of this confrontation are learned from and the systemic knowledge updated.

It is of interest to note that a 'consumption' process is no direct part of the picture developed here. It is obviously of utmost importance that individual market participants can use the output of the market processes for both essential maintenance and pleasure. And the attitudes of market participants toward these goods and services are expressed in their preferences, which are one of the two aspects of the environment to which the system adapts. So, while from the perspective of an individual consumption is a vital process, from the perspective of the system it is a side-effect, although one without the indirect effects of which the system could not function.

V. ASSESSMENT

The market system process organization presented here is obviously an idealization. No detail is given as to how the fundamental constraints of property and contract are to be implemented and maintained, and how tight these constraints would have to be in order for the essential epistemic processes to proceed effectively. No detail is given about the structure of the production process[29] and of the various firms, differing in size and organization, through which entrepreneurial plans are implemented.[30] And no detail is given as to how much the exchange, entrepreneurship, and production processes can tolerate external interference with their functioning and still fulfil their epistemic function.[31] The system is presented as fully formed; no indication is given as to how it could have evolved from simpler and less potent arrangements. All of these shortcomings are grist for many mills of future work.

But, for the time being, highlighting the process organization has some virtues—it relates and puts into context some important observations and hypotheses about the functioning of the market system, showing them to be consequences of the fundamental process organization. These involve aspects of economies which appear to be of obvious significance for understanding how markets actually work, but yet have no obvious place in mechanical macroeconomic models featuring quantities in equilibrium.[32] In fact, the history of economic thought is replete with observations, studies, and hypothesis centering on such phenomena as entrepreneurship and the epistemic characteristics of markets, all of which clearly say something important about functioning of markets, and yet none of this finds its way into macroeconomic theory. They, as Klein (2008, p. 175) puts it, 'are viewed as interesting, but idiosyncratic, insights that do not easily generalize to other contexts and problems' and certainly present difficulties in rendering in mathematical terms. For example, consider the following classics:

- Schumpeter's vision of the entrepreneur as 'the pivot on which everything turns'.[33] It is the entrepreneur, according to Schumpeter, whose innovations drive economic development. Entrepreneurship is a process that is both creative, resulting in the emergence of new production possibilities, and destructive, rendering obsolete existing methods and products and the firms which depend on them for profitability.[34] Significantly, it is portrayed as a process internal to the economic system. Although Schumpeter (1954, p. 529) was correct in noting that economists had never 'accomplished the impossible feat of overlooking the most colorful figure in the capitalist process', modern macroeconomics comes very close to that accomplishment, rendering entrepreneurial effects as unexplained technological shocks impinging on the economic system from without.
- McCloskey's explanation of the 'great enrichment'. McCloskey (2010) focuses on what she correctly thinks should be the major phenomenon requiring economic explanation: the increase of real income per head since 1800 by a factor of something between 16 and 100 (but probably closer to the latter), an increase which (together with its timing) is not explainable in terms of either supporting institutions or efficiency increases. After analyzing, and rejecting, a long list of possibilities, her explanation (p. 394) is that 'a pair of positive externalities', specifically, 'a new dignity for the bourgeoisie in its dealings and a new liberty for the bourgeoisie to innovate in economic affairs' which emerged in Holland and England in the 1700s are the crucial factors at play. The ability for entrepreneurs to be tolerated and accorded sufficient respect and forbearance meant that practically creative people could respectably, and with expectation of profitably, attempt to implement their innovative plans and conjectures. That the economic growth unleashed by this freeing of the entrepreneurial process was unprecedented underlines the essential role of that process in the functioning of the market system.
- Mises' 'problem of economic calculation'. Mises (1920) explained in detail the indispensability of market prices for entrepreneurial assessment of possible production plans, a process he called 'economic calculation'. He pointed out that the ability to 'calculate' based on market prices (p. 14) 'affords us a guide through the oppressive plenitude of economic potentialities … Without it, all production involving processes stretching well back in time and all the longer roundabout processes of capitalistic production would be gropings in the dark'.[35] In short,

without a price structure which is the result of market activity, a rational system of production processes is not possible.

- Hayek's 'knowledge problem'. Hayek (1945, pp. 519-520) identifies 'the economic problem of society' as 'a problem of how to secure the best use of resources known to any members of society, for ends whose relative importance only these individuals know', i.e., 'a problem of the utilization of knowledge not given to anyone in its totality'. He (pp. 526-527) points to the price system, the process of monetary exchange under the norms of property and contract, as ameliorating the problem by providing the function of 'communicating information … which enables individual producers … to adjust their activities to changes of which they may never know more than is reflected in the price movement'. The process is one of learning about environmental inputs, generating knowledge about environmental changes, not through analysis by individuals but as the emergent result of continuous exchange transactions.

The picture of market process organization developed here integrates all of these prescient contributions into a single schema. The central importance of the entrepreneurial process described by Schumpeter, the potency of which for productive economic growth and prosperity is pointed to by McCloskey, is linked to, and made possible by, the existence of the price system as explained by Mises, which in turn is characterized by Hayek as the result of a process in which the local, idiosyncratic, and dispersed knowledge of individuals of the state of their environment as they assess it is rendered into a useful form that is widely accessible. The closed circle of the processes of entrepreneurship, production, and exchange, anchored by an internally generated model of the environment, constitutes the basic organization of the market as an anticipatory system.

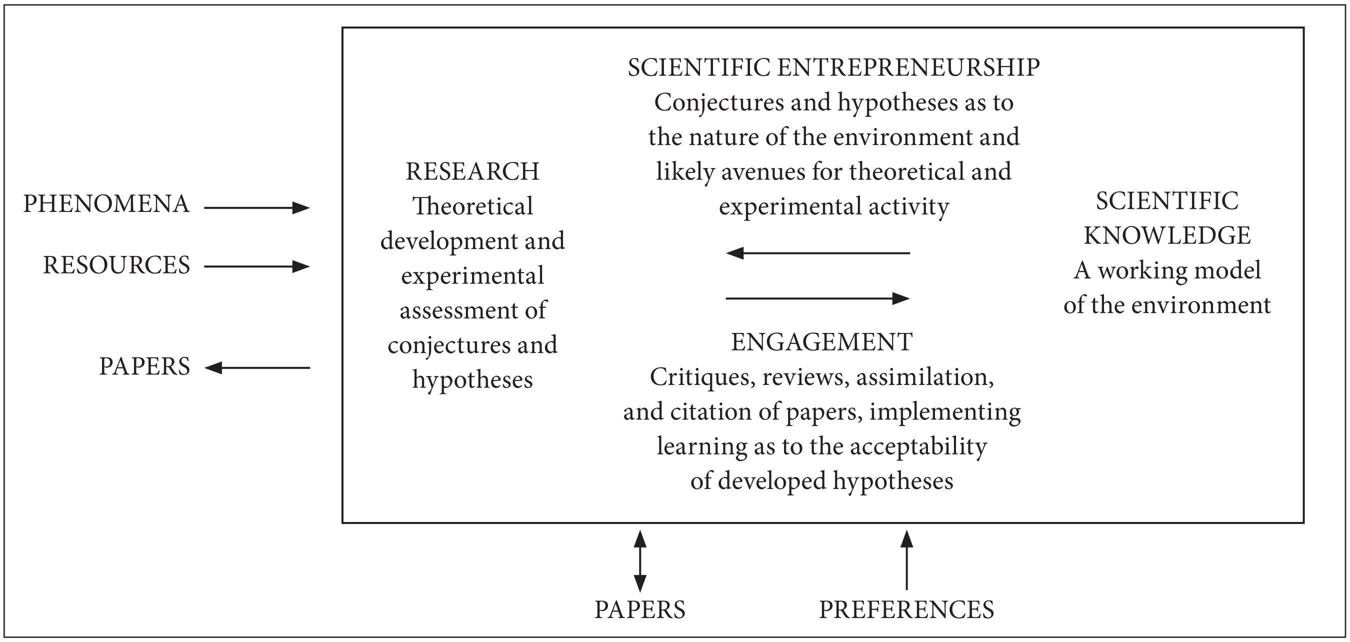
Hayek (1945, p. 528) expresses his conviction that his 'knowledge problem' considerations apply in social contexts other than markets: 'The problem which we meet here is by no means peculiar to economics but arises in connection with nearly all truly social phenomena … and constitutes really the central theoretical problem in all social science.' If he is right, and if the concentration on process organization deployed here, a generalization of Hayek's approach, is of use in extending the understanding of market systems, then it is a reasonable conjecture that it could be of use in conceptualizing and understanding other prominent and long-lasting social arrangements. The arrangements of modern science,[36] which are characterized not by property, contract, and exchange norms in the market sense, but by norms of publication, citation, and correspondence with observation, is an obvious candidate. While what follows is no more than a suggestive sketch, it makes the important point that the potential applicability of process-centric models is not limited to markets but might usefully be applied to the understanding of other major social arrangements.

VI. SCIENCE PROCESSES

It is no surprise that learning and anticipation should play a large part in any description of the activity of science, but in the usual descriptions of science the processes of learning and anticipation refer to the activity of individual scientists. But here, the focus is on learning and anticipation as systemic processes—processes which, although obviously involving individual activity, operate at the system level and whose emergent effects are not under the control of any individual.

A 'science system', as defined here in very general terms, is a complex of people in their roles of researchers, experimenters, theorists, and reviewers engaging in activity mediated by the institutions of publication and citation.[37] Observable as a result of continuous publication and citation interactions is the emergence of a structure of scientific knowledge—a set of generally accepted theories and methods which, while usually stable in the short run within small limits, can change in reaction to new findings and reassessments. The body of scientific knowledge is the structure within the system that serves as a model of the system's environment—a model that is continuously updated by environmental feedback transmitted by the agency of repeated publication and citation transactions in papers[38] through which scientists engage with each other.[39] Scientific entrepreneurs within the system rely, at least in part, on this existing knowledge base in imagining conjectures and hypotheses and in assessing the feasibility of these hypotheses as scientific contributions, and thus act as an anticipatory process affecting the system's research propensities.

Given these identifications of science process and structure, the overall process organization of the science system can be illustrated as follows:



Just as was done for the market system, this picture of science is focused on functional organization, and represents the system of science as an anticipatory system incorporating and maintaining a working model of its environment, a model which can be accessed internally within the system to project the anticipated effects of future actions taken by the system, providing an organization within which its component scientists can combine creatively within the system's constraints in ways that are not possible for them when acting independently.

The external 'material' elements (both tangible and intangible) impacting the science system are represented here as the following sets (the memberships of which will change in the course of the system's operation):

- The set of phenomena A in the environment which are observed in the course of research.
- The set of resources R which enter the system from the environment.
- The set of subjective preferences S of scientists. These preferences are not arbitrary, although they will differ across scientific domains and between schools within those domains. In the physical sciences, particularly, there is a strong norm supporting a preference for correspondence with observation.

Elements produced within the system are represented in terms of the following sets:

- The body of scientific knowledge M which functions as an updatable model of the environment, as experienced by the system in terms of A, R, and S.
- The set of output papers O produced by scientists explicating their work.
- The set of conjectures or hypotheses C developed by scientific entrepreneurs.

The processes which constitute the dynamic elements of the system are as follows:

- **Engagement (x).** Out of repeated publication and citation between scientists (acting according to their individual subjective preferences), there emerges the structure of scientific knowledge M, i.e., **x**: O, S → O, M.
- **Scientific Entrepreneurship (e).** This is a function of some scientists which, by projection based in part on current scientific knowledge, generates conjectures which act as dispositions to change elements of the system's research activity, i.e., **e**: M → C.
- **Research (p)**: The development of entrepreneurial hypotheses and the experimental confrontation of their deduced consequences with environmental phenomena, a mapping from hypotheses, phenomena, resources, and papers to papers, i.e., **p**: C, R, A, O → O.

In summary, **x** uses O to produce M, **e** uses M to produce C, and **p** uses C to produce O, all with the aid of, and conditioned by, the external influences A, S, and R.

As with the market system, it is the purposeful agency of the scientists, in the course of acting according to their subjective preferences and motivations,[40] which provides the motive force animating the processes in the system. Scientists interact by participating in engagement, entrepreneurship, and research under the institutions of publication and citation—a set of processes which, given the system's material openness, are each necessary for the function of the others, and which together are sufficient to enable the system's existence as a self-maintaining entity.

It would take a serious excursion into the philosophy and sociology of science to flesh out and assess the potential of this process-organizational picture of science for the understanding of the social activity of science.[41] But preliminary work indicates that some individual and unconnected claims of postpositivist philosophy of science—including constrained relativism, strong antifoundationalism, Duhemian underdetermination, inescapable theory-ladenness, and limited incommensurability—can be related and put into the context of a nonnormative and naturalistic philosophy of science with the help of such a process-oriented picture.

VII. SUMMING UP

Applying, by analogy, the insights of organicist biologists to the study of social systems provides a way of understanding such systems in terms of the organization of their constituent processes—a very different approach from the usual one of attempting understanding (or prediction) in terms of equilibrium states described in material terms. And what becomes very clear from this focus on process organization is the realization that certain processes (in particular, those that implement learning and anticipation) which appear as essential in the sustained operation of these systems either do not feature at all, or feature only in a stylized form, in current theoretical models of the systems as a whole.

The analysis of systemic organization described here is pitched at a very abstract level, and certainly needs to be extensively fleshed out in order to understand the many variations within the basic process types and to model the operation of the supporting processes on which the functioning of the higher-level processes depends. In the case of markets, a great deal of work along those lines has been done already under the rubric of market process economics; what the contribution in this paper offers is an encompassing theoretical structure into which the scattered results can be integrated. In the case of science, there is relatively little in the literature on the economics of science that would be useful in augmenting a process-oriented picture,[42] but the work of sociologists of science from Merton on, as well as some theorizing in the 'sociological' strands of the philosophy of science,[43] when put in the context of the picture developed here, should provide considerable material for a fuller process-centric theory of science.

Rosen's (1991, pp. 119-120) epigram for encapsulating his approach to understanding biological systems was 'throw away the matter and keep the underlying organization'. While this is obviously a radical departure from the usual way in which systems are conceptualized, it is not an unscientific move for, as he put it: 'The organization of a natural system … is at least as much a part of its material reality as the specific particles that constitute it at a given time, perhaps indeed more so. As such, it can be modeled or described in full accord with Natural Law [i.e., scientifically]; the resulting formalisms have at least as much right to be called images of material reality as any reductionistic model based on states and dynamical laws.' If he is right, and understanding process organization is a path to understanding biological systems—in fact, the key to understanding how they work—then there is a reasonable chance that this insight can be useful in the quest to understand social systems. I hope that the work here can bring that possibility to notice.[44]

NOTES

1 For a short summary of the influences on Walras in the development of his system, see Jaffe (1983). For an assessment of the influence of Walras on the development of macroeconomics, see Kirman (2011a). For a detailed and highly critical assessment of the mathematization of economics, see Mirowski (1989). For histories of the development of modern mainstream macroeconomics from Keynes to the present day, see Garrison (2001, pp. 18-23) and DeVroey (2016). DeVroey (p. 380) observes that 'the rise of DSGE macroeconomics amounted to giving prominence to internal consistency over realism. I find this line defensible yet it bears a heavy price, namely that macroeconomists must refrain from claiming that the policy conclusions of their models have a direct policymaking bearing'. For recent critical assessments of modern macroeconomics, see Romer (2016) and Glasner (2018). The seriousness of the critiques can be gauged from a quote from Romer's abstract: 'Their models attribute fluctuations in aggregate variables to imaginary causal forces that are not influenced by the action that any person takes. A parallel with string theory from physics hints at a general failure mode of science that is triggered when respect for highly regarded leaders evolves into a deference to authority that displaces objective fact from its position as the ultimate determinant of scientific truth.'

2 The manifestly *ad hoc* nature of these concessions to mathematical tractability has been one inspiration for the development of agent-based models which, through simulation, allow for repeated individual interactions between heterogenous agents. For an introduction to the large literature which has developed in this vein, see Tesfatsion (2002, 2006); for an early example of the modelling technique, see Epstein & Axtell (1996). Of relevance to the current work is that such models demonstrate the possibility for self-organization in markets and other social and biological systems, a line of thought which has been developed extensively by Kauffman (1993). Related to, and generally compatible with, these new approaches is complex systems theory. See Foster (2005) for a useful taxonomy of types of complex system and for a discussion of some of the implications of replacing standard macroeconomics with network theory.

3 For an historical treatment of market process theories, see Boettke & Prychitko (1998). For a treatise on evolutionary economics, see Dopfer & Potts (2007) and, for a history of the subject, see Hodgson (1995). For an overview of process theory in the Austrian tradition, particularly the seminal contributions of Mises and especially Hayek, see Kirzner (1997). For a discussion of both Schumpeterian and Kirznerian approaches to entrepreneurship and an application and extension of Kirzner's theory of entrepreneurship, see Harper (2003), and for a summary of recent developments in the economics of entrepreneurship, see Parker (2004) and Klein (2008). For a treatment of expectations based on Hayek's work, see Butos & Koppl (1993). For a game-theoretic treatment of learning from feedback see Teck, Lim, & Camerer (2006, pp. 323-325), and for a discussion of the applicability of cognitive science to consumer choice, see Bartels & Johnson (2015). For an analysis of the role of confidence in the context of the Great Recession, see Koppl (2014). For an explanation of regime uncertainty and its role in the Great Depression, see Higgs (1997).

4 For a more extended historical overview of the development of the role of process organization in biology, with references to the historical literature, see Mossio *et al* (2016).

5 Aristotle (350BCa) emphasized the necessity for studying the parts of an organism with an eye to explaining the organizational interdependence of their parts in achieving their purpose: 'Now that with which the ancient writers, who first philosophized about Nature, busied themselves, was the material principle and the material cause. … But if men and animals and their several parts are natural phenomena, then the natural philosopher must take into consideration not merely the ultimate substances of which they are made, but … must examine how each of these comes to be what it is, and in virtue of what force. … For the formal nature is of greater importance than the material nature. … It is plain, then, … that the true method is to state what the definitive characters are that distinguish the animal as a whole; to explain what it is both in substance and in form'.

6 In Kant's (1790) words: 'For a body then which is to be judged in itself and its internal possibility as a natural purpose, it is requisite that its parts mutually depend upon each other both as to their form and their combination, and so produce a whole by their own causality;

while conversely the concept of the whole may be regarded as its cause according to a principle (in a being possessing a causality according to concepts adequate to such a product). In this case then the connexion of effective causes may be judged as an effect through final causes.'

7 For a history of the development of 'systems thinking' in early 20th century biology, embryology, and psychology see Drack *et al* (2007).

8 Bickhard (2000, p. 12), in a discussion of the difficulties of accounting for the causal properties of emergent phenomena within a substance metaphysics, proposes that 'organization is not something superimposed on a more basic level of reality; it is a necessary aspect of all reality. So, delegitimating process organization as a potential locus of emergence renders all reality epiphenomenal, because there is no reality that is not constituted as process organization.' In particular, according to Campbell & Bickhard (2011, p. 31): 'Biological systems—including humans—are not substantial entities ("things" in the thick sense) whose constituents are cells (smaller things), which in turn (after a few more reductions) are constituted out of elementary particles. They are open, organized action systems, in essential interactions with their environments, such that we cannot say what they are without taking those interactive processes into account.' 'Process philosophy', however, is not a new trend—its roots go back at least to Heraclitus. But it has gained interest in modern times, firstly due to the impact of the theory of evolution, secondly due to the efforts of biologists (including Bertalanffy and Rosen) to study and explain the dynamic phenomena of self-organization, emergence, and adaptation, and thirdly due to recent developments in quantum field theory which point to a process ontology being more fundamental than a substance one. A recent influential treatment of process metaphysics is that of Rescher (2000). For a useful overview of and commentary on process philosophy, see Seibt (2018).

9 See Bertalanffy (1968, pp. 156-160). Georgescu-Roegen (1976, p. 53) has also invoked thermodynamics to emphasize the open nature of economic systems: 'The economic process is a partial process that, like all partial processes, is circumscribed by a boundary across which matter and energy are exchanged with the rest of the material universe… From the viewpoint of thermodynamics, matter-energy enters the economic process in a state of low entropy and comes out of it in a state of high entropy'. For a fine discussion of 'openness' and 'closedness' particularly with respect to economic systems, see Chick & Dow (2005).

10 According to Piaget (1967): 'The central ambiguity is that of the "open system", for, if system exist, then something like a closure intervenes, which has to be reconciled with the "opening".…The opening then is the system of exchanges with the environment, but this in no way excludes a closure, in the sense of a cyclic rather than a linear order… [and so] we are confronted by a closed cycle, which expresses the permanent reconstitutions of the [material and dynamic] elements [of the structure], and which is characteristic of the organism; but each interaction… at the same time represents an opening into the environment as a source of aliment.'

11 See Aristotle (350BCb). The following simple example, dealing with the construction of a house, may be helpful in understanding the Aristotelian categories. The material cause of the house is the physical matter out of which the house is built, the formal cause is the architect's plan for the house, and the efficient cause is the builder's construction activity. The final cause is the use of the house as a home, which can be characterized as the purpose of the house. Note that the notion of 'purpose', while sounding natural enough when applied to biological entities, does not fit well into the normal Newtonian framework of physical science, where present states are determined by past states only and not future states such as, in the present example, the homey services of the completed house.

12 See Rosen (1973). Rosen expressed his later work in the notations of category theory, a very general branch of mathematics which deals with collections of specific mathematical objects (sets, maps, groups, vector spaces, etc.) and the transformations between them. The focus in category theory is on the relationships between the objects rather than the objects themselves. For a formal exposition of category theory in a biological context, heavily dependent on Rosen's work, see Louie (1983).

13 For assessments of Rosen's contributions, see Louie (2006, 2008, 2010), Cornish-Bowden *et al* (2007), Pattee (2007), and Cárdenas *et al* (2010). Debates continue about some of Rosen's more controversial claims, such as that closure to efficient causation is a sufficient criterion for life, and that living systems are not machines and are not simulable in finite time—see Wells (2006),

Gatherer & Galpin (2013), Zhang *et al* (2016), and Siekmann (2018). However, Rosen's work is a foundation for ongoing research into biological systems—see Montévil & Mossio (2015) and Mossio *et al* (2016). For a survey of applications of Rosen's work, see Cárdenas *et al* (2017).

14 For brief history of economists employing biological analogies, citing instances going back to Mandeville, Quesnay, and Adam Smith, see Callejas (2007). See Hodgson (1998) for a comprehensive series of articles on the history of evolutionary economics. Probably the most disturbing critique of biological metaphors in social theory was that of the historian Hofstadter (1944), who successfully attached the epithet 'social Darwinism' to free-market economics, and who opined that 'such biological ideas as the "survival of the fittest", whatever their doubtful value in natural science, are utterly useless in attempting to understand society; that the life of man in society, while it is incidentally a biological fact, has characteristics that are not reducible to biology and must be explained in the distinctive terms of a cultural analysis'. But see Leonard (2009) for a perceptive study of Hofstadter's inconsistencies and misunderstandings—and his honesty in calling out the eugenicist and racist aspects of progressive era social science. In economics, Penrose (1952), citing Hofstadter favorably, famously addressed the biological analogies employed by the 'biological economists' Boulding and Alchain, who, she said, 'view firms as organisms and conclude that they grow like organisms', and critiqued them on the grounds that their 'variant of the growth approach leaves no room for human motivation and conscious human decision'. But apparently, according to Levallois (2011), her objection to biological analogies later mellowed, and she cited favorably the work of the evolutionary economists Nelson, Winter, and Hodgson.

15 That this was a consistent feature of Marshall's thought is evident from other statements of his, for example (1898, p. 314), 'in the later stages of economics [i.e., as the subject develops] better analogies are to be got from biology than from physics; and, consequently, that economic reasoning should … gradually become more biological in tone'.

16 According to Rosen (1975, pp. 68-69), 'we have much to learn about the nature of our own social technology from a study of comparable processes occurring in biological systems. Particularly in the study of adaptive mechanisms, it is important to avail ourselves of the experiences preserved for us in the biological record, when translated into an appropriate social context.'

17 For treatments of various social arrangements as adaptive systems see, for example, Kauffman (1993, pp. 395-402), Buckley (1998), Elder-Vass (2010), McQuade & Butos (2009), and Ruhl (2008). In economics, there have been many papers in recent years dealing with complex adaptive systems—see, for example, Krugman (1995), Tesfatsion (2006), Kirman (2011b), and Arthur (2015). The idea is also clearly in Hayek—see, for example, Hayek (1967, pp. 66-81), where he asserts that 'there is no reason why a polycentric order in which each element is guided only by rules and receives no orders from a center should not be capable of bringing about as complex and apparently as "purposive" an adaptation to circumstances as could be produced [in a centralized system]'.

18 See Rosen (1975). Also, in his introduction to his major treatise on anticipatory systems, Rosen (1985, pp. 4-5) noted the possibility for biological metaphors to be applied in social theory: 'It is plain, on the face of it, that many tantalizing parallels exist between the processes characteristic of biological organisms and those manifested by social structures or societies.' One upside he cited for the employment of such parallels was that since 'it is hard for us to conceive what an external observer of our society as a whole would be like … [but] by exploiting biological experience, obtained from a standpoint of an external observer, we could … develop entirely new insights into the properties of our social systems.'

19 It is worth pointing out that the human brain is a biological anticipatory system, and its high-level functional organization can be represented by such a system diagram, with 'output' understood to include actions manipulating aspects of the environment and 'anticipation' referring to what economists usually call 'expectations'. See McQuade (2019). Interestingly, the economist Hayek (1952) was one of the first to describe the functional aspects of the brain in these terms, showing how a mutable model of the environment could be maintained and updated within a complex neuronal structure and used to create dispositions for action in particular circumstances based in part on past experience. Hayek's model of the mind as a 'sensory order' is fundamentally a process (rather than a substance) model. For a comprehensive description and assess-

ment of Hayek's work in this area, see Vanberg (2017), and for shorter explanations see Butos & Koppl (1993) and McQuade & Butos (2005). For work applying the 'sensory order' analogy to social arrangements in ways complementary to the analysis in this paper, see McQuade & Butos (2005), McQuade (2006), and Horwitz (2008).

20 In line with the high level of abstraction that characterizes this discussion, the legal, security, and financial institutions which underpin the processes of production and exchange and are vital for their proper functioning are not included here—they are assumed to be operative in the background and to function adequately enough for it to be unproblematic to focus only on the higher-level processes they support.

21 The term 'emergent' is used here informally to refer to a systemic property which arises from the interactions of system components. But it is not a simple concept. For an examination of the subtly different ways in which the concept is applied in economics and social theory, see Harper & Lewis (2012) and the articles in the volume for which that is the introduction.

22 Of course, other widely understood appraisals, like brand reputation, also emerge in this way, and calling the emergent mapping 'the price structure' is not intended to imply an oversimplification of its complex structure. Less obvious, but no less important as a component of that mapping is what Lachmann (1956, p. 53) has called 'the capital structure', the sensitive and shifting arrangement of capital goods as entrepreneurially appraised complements and substitutes for each other. The identification of the capital structure as a component of a mutable model of the environment is consistent with Horwitz's (2008) analysis.

23 The price structure has been characterized as a 'classification' of environmental inputs—see McQuade (2006, p. 62): 'The … transactions (characterized by transfers of goods and observable exchange prices) between the market participants … are induced by stimuli from environmental conditions conditioned by the preferences and creativity of the market participants themselves. They … result, indirectly, in a classification of the various stimuli currently impinging on the market system, a classification embodied in the array of market goods and their market prices.' A classification of a set of phenomena is no more nor less than a type of model of the phenomena.

24 See McQuade & Butos (2005, pp. 343-344): 'The market has, in effect, functioned as an anticipatory mechanism triggered by a current stimulus … that has conditioned it to respond in ways that take account of the future. … While it is clear that part of the process involves regular human insight into the future, it is at the market level … that we observe a manifestation of the anticipatory aspects of the system as it responds to environmental change. … For the market economy, these adjustment responses are instantiated by market mechanisms in which entrepreneurial activity and time markets play decisive roles.'

25 As Harper (1996, p. 286) puts it, highlighting the bottom-up nature of the process in Popperian terms: 'the refutation of entrepreneurial conjectures is a highly decentralized activity which does not involve an organized group or collective body representing consumers. Rather it results from a sufficiently large number of targeted consumers individually deciding not to purchase an entrepreneur's product offering'.

26 In other words, the market is a 'fourth order complex system' in Foster's (2005, pp. 876-877) taxonomy.

27 More specifically, these are sets of processes. In an actual market economy, there are a great many processes of each type, differing in detail, but each having in common the basic function of its type.

28 See Popper (1963, p. vii): 'The way in which knowledge progresses … is by unjustified (and unjustifiable) anticipations, by guesses, by tentative solutions to our problems, by conjectures. These conjectures are controlled by criticism; that is, by attempted refutations, which include severely critical tests.' See also Popper (1972). In Harper's words (1996, pp. 290-291): 'The competitive market process is a s*pontaneously evolved* set of institutions which facilitates the testing of entrepreneurial conjectures and the generation of new structural knowledge. The fact that the market process is a learning process which is spontaneous in origin means that it has been created from forces within the system (i.e., its structure is endogenous). It has formed itself through a process of selective evolution—it is a self-organising system.'

29 The structure of the production process, particularly with regard to the nature of markets for capital goods and their facilitation of intertemporal exchange, is the focus of a distinctively Austrian macroeconomics. See Garrison (2001).

30 There is a huge literature on the economics of the firm. See Hart (1989) for a survey of the more prominent approaches, and Teece (2017) for a more recent appraisal. Hart complains that 'the portrayal of the firm in neoclassical economics is a caricature of the modern firm', and Teece observes that 'there is little effort to look at particular firms, their histories, and organizational and technological issues in a systematic, time-aware manner'. It is possible that the theory of the firm could benefit from the theory of anticipatory systems in which the firm is the system of interest, since business success depends both on learning customer needs and innovating ways in which these needs might be met.

31 Government operates on the market system by imposing restrictions, beyond those constraints of property and contract on which the system's operation relies, on the processes of exchange, entrepreneurship, and production. In general, these are done piecemeal and with local objectives; they are not done (and cannot be, in the absence of a realistic theory of the economy) for the purpose of increasing the epistemic performance of the economy. In fact, observations of the unintended consequences that, sooner or later, follow such restrictions would indicate that they tend to have the opposite effect. Adam Smith was undoubtedly correct in his observation, recorded in Sinclair (1831, p. 391), that 'there is a great deal *of ruin* in a nation', but getting a handle on just how much, and why there might be limits, should be a question of great concern to economists.

32 As Schumpeter (1942, p. 86) eloquently put it, in the context of describing how the standard economic theory treats 'competition within a rigid pattern of invariant conditions, methods of production and forms of industrial organization' in an equilibrium setting, and thereby misses the dynamic creative and destructive aspects of real-world competition: 'Now a theoretical construction which neglects this essential element of the case neglects all that is most typically capitalist about it; even if correct in logic as well as in fact, it is like *Hamlet* without the Danish prince.'

33 See Schumpeter (1954, p. 530): '[Although he] did not see all its analytic possibilities [J.B. Say] did realize, to some extent, that a greatly improved theory of the economic process might be derived by making the entrepreneur in the analytic schema what he is in capitalist reality, the pivot on which everything turns.'

34 See Schumpeter (1942, p. 83): '[Capitalism is a process] that incessantly revolutionizes the economic structure *from within*, incessantly destroying the old one, incessantly creating a new one. This process of Creative Destruction is the essential fact about capitalism. It is what capitalism consists in and what every capitalist concern has got to live in.'

35 Mises (1920, pp. 34-35) exposed the utopian nature of socialist theorizing: 'All socialist systems … proceed from the assumption that in a socialist society a conflict between the interests of the particular and general could not possibly arise. Everybody will act in his own interest in giving of his best because he participates in the product of all economic activity. … But even if we for the moment grant that … each individual in a socialist society will exert himself with the same zeal as he does today in a society where he is subjected to the pressure of free competition, there still remains the problem of measuring the result of economic activity in a socialist commonwealth which does not permit of any economic calculation. We cannot act economically if we are not in a position to understand economizing.'

36 By 'modern science' is meant science carried out under the arrangements that have evolved from those explicitly developed at the Royal Society in England during the second half of the 17th century. Merton (1973, pp. 191-203 & 460-496) has noted the coincidence of the rise of scientific and technological activity in England and the formalized communication between scientists which took shape upon the founding of the Royal Society and the inauguration of its journal, the Philosophical Transactions. Prior to that, scientists such as Bacon had advocated that science be an endeavor pursued for the common good of society and not for personal credit. The specific mechanism introduced by Henry Oldenburg, the secretary of the Royal Society, was access to publication for scientific papers, enabling the author to receive personal credit and identification of priority and thus eliminating a major reason why authors might withhold access to their work. To this function was soon added the feature of referee-based certification, as Oldenburg turned to other society members for advice on acceptance of papers when the material was outside his competence to evaluate. See also Hull (1988, pp. 323-324) and McQuade & Butos (2003, p. 141).

37 In line with the high level of abstraction that characterizes this discussion, the legal, security, and financial institutions which underpin the processes of research and publication and are vital for their proper functioning are not included here—they are assumed to be op-

erative in the background and to function adequately enough for it to be unproblematic to focus only on the higher-level processes they support.

38 By 'papers' is meant not only reviewed papers published in journals, but any vehicle through which scientists can engage each other's work, including conference presentations, circulated working papers, speeches, podcasts, and internet blogs.

39 See Butos & McQuade (2012, p. 2): 'Scientists publish speculations and observations; other scientists who find these useful to their own work (or who wish to criticize them) cite them; the citation feeds back to affect the reputation of the publishing scientist; and a scientist's reputation not only affects the notice given to his future publications and citations but also his ability to attract funding or to advance in academic position. This recursive set of procedures and feedback loops, hereafter referred to as "PCR" (for Publication-Citation-Reputation), implements the knowledge generating characteristic of the scientific order. In this picture, "scientific knowledge" is not the knowledge of individual scientists; it is the end result of the PCR processes repeatedly acting on individual scientific contributions, ignoring, altering, merging, selectively abstracting, and reinterpreting them in the process.'

40 Including, among other motivations, the motive to enhance one's scientific reputation, a prized benefit for which participation in the system's processes is a prerequisite, since reputations emerge as a side-effect of the system's transactions.

41 Preliminary work to that end is attempted in McQuade (2010).

42 Work in the economics of science tends to view science through a market lens, portraying the activity of science as transactions in ideas, and typically identifying inefficiencies due to the nonrivalrous and nonappropriable nature of ideas. For a survey of work in the economics of science, see Stephan (1996); for a brief critique of the market approach to science see Butos & McQuade (2006, pp. 185-193).

43 For Merton's classic contributions to the sociology of science, see Merton (1973; 1996). Interesting work with some process orientation in the philosophy of science includes Kuhn (1962), Barnes & Bloor (1982), Popper (1984), and Goldman (1999).

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