ECONOMICS FOR A CREATIVE WORLD*
(and a response to comments)

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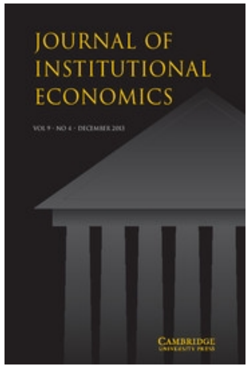

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Abstract. Drawing on current biology, we argue that the phase space of economic evolution is not stable. Thus, there are no entailing laws of economic dynamics. In this sense, economic dynamics are creative and the economy is not a causal system. Because economic dynamics are creative, the implicit frame of analysis for the econosphere changes in unprestatable and non-algorithmic ways. New-venture, social, and political entrepreneurs solve the frame problem of the econosphere. Economic evolution is unpredictable, not entailed, and the number of things traded ('cambiodiversity') increases over time. Our metatheoretic framework points out how institutions, entrepreneurs, and disparate actors enable what we call 'novelty intermediation'. We provide examples of novelty intermediation from Rennaissance Italy to Silicon Valley. Our framework does not automatically provide clear policy prescriptions in part because our main result is negative. It may nevertheless provide a useful prolegomenon to a future economics fit for a creative world.

> [T]he matter with which the chemist deals is the same always: but economics, like biology, deals with a matter, of which the inner nature and constitution, as well as the outer form, are constantly changing (Alfred Marshall).

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1. Introduction

A rigorous examination of some common modeling practices in economics may suggest the desirability of moving away from mechanistic models and toward a more evolutionary and institutional approach to economic theory and policy.

Many of the more important standard models in economics are mechanistic. Often inspired by physics, such models represent economic dynamics as the unfolding of a process fully described, up to a stochastic error term, by a master set of equations or an evolution function. The microeconomic models of general equilibrium theory and the macroeconomic models of dynamic stochastic general equilibrium (DSGE) are important examples. In such models, economic dynamics are law-governed in a strong mechanistic sense: in principle at least, there is a set of equations that embodies the system's laws of motion up to an error term. The typical model used in policy evaluation, including macroeconomic policy evaluation, is thought to be a low-dimensional approximation to a possibly high-dimensional reality. If we could have a set of equations correctly describing the high-dimensional reality, it might not be analytically solvable or computationally tractable. The low-dimensional model, however, is a simplified approximation that is constructed to be tractable. Model calibration ensures that the approximation will hold good in future periods, allowing reliable policy recommendations to be based on the model.

This modeling strategy is generally satisfactory only if the predictions such models can generate are reliable enough and specific enough to guide policy. It is generally sufficient only if it is not necessary to describe in detail the institutions governing social and economic life and only if there are no particular limits to prediction in economics. We argue, however, that there is a sense in which economic dynamics are 'creative' and that this 'creativity' limits the usefulness of standard mechanistic models in economics. If we are right, then standard mechanistic models may have less to say about economic dynamics than their widespread use might suggest. In this case a greater attention to institutional particulars may be in order.

We question the cogency of the standard approach to economic analysis. If economic dynamics are 'creative' in a sense we will specify, then there can be no low-dimensional approximation to the high-dimensional unmathematizable reality. The underlying dynamics of the econosphere continually produce novelty and thus change the phase space, that is, the space of pertinent observables and parameters, within which the system unfolds. The phase space of economic activity is not stable. But without a stable prestatable phase space, tractable models will not generate the reliable counterfactuals required for the standard sort of policy analysis. Indeed, no set of equations, whether tractable or not, can be written or track this sort of creative dynamics even in principle.

Our discussion of creative dynamics resembles other discussions of similar themes, including Dopfer (2005), Hayek (1967, 1978), Hodgson and Knudsen

(2010), Nelson and Winter (1982), Potts (2012), Shackle (1969), and Witt (2009). Witt (2009) in particular takes a very similar approach. Bunge (2009) emphasizes the incompatibility between novelty and a stable phase space, as do we. Our discussion may have at least three advantages over past treatments. It probably contains a more detailed consideration of the mathematical structure of standard methods than other similar critiques. In particular, we have given more attention to evolution in the phase space. Second, we link our critical treatment of standard models to the evolutionary logic of what Hodgson and Knudsen (2010) call Generalized Darwinism. Finally, our treatment locates novelty production within the process of evolution, rather than viewing it as exogenous or attributable primarily to individual creativity. This last feature of our analysis seems to be unusual or unique, and we will discuss the 'positive' implications of this move below. Briefly, this move lets us explain why 'creativity' would not come to an end even if it were only the recombination of existing elements. It also draws our attention to what we shall call 'novelty intermediation', which relates to the notion of 'novelty-bundling markets' discussed by Potts (2012) or the 'market for preferences' of Earl and Potts (2004). We will note that governments and businesses, as well as households may seek the services of novelty intermediaries.

We are conscious of the changes in recent decades that have weakened the hold of the old neoclassical orthodoxy of the post-war period. As Colander *et al.* (2004) have chronicled, mainstream economics has been greatly influenced by complexity theory (also see Durlauf, 2012). It has become more inductive and open. But mainstream economists still tend to be attached to mathematical methods that are not always well suited to a creative economy, as with DSGE models. Much of the mainstream matches our description of orthodoxy only too well, especially in macroeconomics. The tools of complexity theory have helped to push practice in the right direction, but further movement in that direction may be good if economic dynamics are creative in the sense we explain below.

We are also conscious of the variety of senses in which a process may be 'law governed' or in which one may speak of 'economic laws'. Our negative results cast doubt on one sense of 'law governed'. It says relatively little, however, about other senses in which economic processes might be 'law governed', some of which may be compatible with our view that economic dynamics can be 'creative' in the sense given below. Indeed, we affirm the existence of an evolutionary logic in the multiplication of goods over time. If evolutionary biology may be said to have 'law-like hypotheses', then so too does the sort of evolutionary economics suggested by our analysis. Such law-like hypotheses do not generally come in the form of specific predictions about the future, for example, that a particular sort of species will emerge in a given time and place. They often come in the form of if-then statements. Such if-then statements, however, are generally recognized as 'laws' or 'law-like' hypotheses.

It may seem unreasonable, even absurd, to reject 'entailment', 'law', and 'cause'. In each case we do so only for a narrow and precisely defined sense of the term. Even though we reject only narrowly circumscribed senses of 'entailment', 'law', and 'cause', we are indeed suggesting a departure from customary modes of thinking about social processes. This departure does not somehow imply that the social world is a magical place where anything can happen and systematic thinking is futile. We affirm the existence of recognizable regularities in social processes such that a science of society is possible. The methods appropriate to that science, however, should not rule out the continual production of novelty and the resulting continual change in the space of observables and parameters within which the system unfolds.

If economic dynamics are 'creative' in some sense, then standard mathematical models cannot reliably predict the consequences of different policies, at least at the level of specificity such models often aim at. Our criticism raises the question of how economics should be done. We discuss what an economics for a creative world might look like. Our discussion is tentative and suggestive. We do not think we can predict the future course of science, which is, after all, a creative process. Nor would we pretend to dictate to others how they must think and what they must say. Having criticized orthodoxy, however, we have an obligation to show that the alternative to that orthodoxy is not silence.

The German historical school and the original American institutionalists claimed that, because of the historical specificity of economic institutions, there were few (if any) universal economic laws (Caldwell, 2005; Hodgson, 2001). But they failed to provide a developed theoretical framework to deal with this problem. Our analysis may contribute to a theoretical framework that is rigorous and scientific without assuming the sort of 'universal law' that fits standard modes of explanation in physics. Our analysis is more metatheoretic framework than applied theory. Institutions will feature strongly in any applied theory, however, that fits our framework. We develop this institutional point in the concluding section.

The Sun is new everyday (Heraclitus).

2. No entailing laws

Economic dynamics are generally treated as 'law governed' in the sense that there is a master set of equations or an evolution function describing the dynamics of the system.[1] Economic theory, on this conception, can be loosely compared to a computer that has been programmed to execute this master set of equations or compute the intended function, or some approximation thereof. The economist feeds a description of initial conditions into the computer and the computer spits

1 Most dynamical systems are just given by a space, a measure, and a function, an endomorphism; in Quantum Mechanics, Feynman gave an evolution function which comes from no equations.

out the future path of the system. When the economist feeds in the hypothetical initial conditions a given policy would create, the computer spits out the future path the system would take if the policy were adopted.[2] We may say that the equations of motion and initial conditions 'entail' the subsequent evolution of the system, and the equations or evolution functions give the 'entailing laws' of the system. Entailment in this sense is a strict condition much like logical entailment: everything that happens as the system unfolds was already implicit in the initial conditions and the assumed laws of motion.

This way of putting things may create the impression that economists are insensitive or unsophisticated about what is predictable. As we noted in the introduction, however, the typical model used in policy evaluation is thought to be a low-dimensional approximation to a possibly high-dimensional reality. The low-dimensional model is a simplified approximation that is constructed so as to be tractable. If economic dynamics are creative in the strong sense we explain below, then this strategy may not work. To help bolster this claim, it may be helpful to distinguish three levels of unpredictability.

First, consider the mathematical description of a double pendulum or of the logistic function, that is the discrete time, continuous space solution of the famous Lotka–Volterra prey-predator model. In both cases, there is a problem with implementing the system on a digital computer. The discrete computational trajectories that can be programmed are necessarily approximations that do not follow the continuous trajectories of the system's equations of motion. When we compute the discrete logistic function, a difference at the 16th decimal (an excellent approximation) is sufficient to produce, after only 50 iterations, different results whose distance covers the full phase space; thus, all information about the system is lost. It would be an error in such cases to think that the system trajectory can be computed: neither the continuous mathematical trajectory, nor the intended physical process is 'followed' or 'shadowed' by the digital computation, even vaguely. (The approximation, at best, goes the other way round, see Pilyugin 1999.)

Second, and more generally, non-linear equations in a pregiven phase space can produce non-analyticity. The derivatives may diverge so that there is no solution. This situation creates bifurcations and homoclinic trajectories, so that we cannot predict or follow the continuous trajectory even in principle. Minor fluctuations or perturbations below observability may break the symmetries (forcing the planet in one direction of the bifurcation or away from the unstable trajectory) in a totally unpredictable way. This holds even apart from considerations of what is computable on a given digital computer. This case has

2 Our description seems to fit mainstream macroeconomic thinking perfectly. The situation in other areas is more complicated, in part because of the influence of complexity theory (Colander *et al.*, 2004). Unfortunately, in our view, it probably remains the best benchmark of mainstream thinking in the main branches of economic theory.

been known since Poincaré's analysis of the 'three body problem', in which two planets orbit a sun and the dynamics are entailed by Newton's equations. Note that all processes that contain some 'interactions' (e.g., the interacting weights in a double pendulum or two planets revolving around a sun) are soundly described by non-linear mathematical systems that present computational problems.

Third and finally, there is our case of a system without a pregiven or prestatable phase space, which we claim characterizes both biological and economic evolution. In such cases both observables and parameters change and we cannot even write entailing equations.[3]

In short, 'algorithmic' means 'deterministic and predictable'. There are plenty of deterministic systems of equations that are not predictable and thus not algorithmic: typically, the non-linear systems we mentioned above. We claim that the econosphere is not even deterministic let alone predictable. The lack of pregiven and prestatable phase space means that we cannot even write the equations that would determine the system.

In the more standard conception of economics, it becomes an essential job of the economist to identify the right set of equations to support prediction and control of the economy. This approach to economics seems to have failed in the Great Recession, provoking Queen Elizabeth to ask a group of economists, 'Why did nobody notice it?' (Pierce, 2008). The British Academy's response to the Queen suggests that mainstream economists are still thinking in terms of entailing laws. 'Everyone seemed to be doing their own job properly', they told the Queen, 'and often doing it well. The failure was to see how collectively this added up to a series of interconnected imbalances over which no single authority had jurisdiction' (Besley and Hennessy, 2009). Rather than questioning the dynamics of the econosphere, this answer questions the organization of economic authorities. If we had had a better organization amongst ourselves, the whole thing could have been prevented.

For economics to be law governed in the sense we have indicated requires that there be a set of equations entailing system dynamics. As we have argued elsewhere (Felin *et al.*, 2013) there can be no entailing laws for the econosphere. Our argument is that of Longo *et al.* (2012), for biological evolution.

In law-governed systems, we can prestate the configuration space or *phase space*, which is given by the set of pertinent observables and parameters. In standard economic models, the system's laws of motion determine the paths of certain variables such as prices and quantities. Typically, each of the n endogenous variables corresponds to an axis in n-dimensional Euclidean space. The system unfolds within that n-dimensional 'phase space'. At least some of the

3 Wolpert (2001) shows that the Laplacean ideal of prediction and control fails even when there are entailing laws no matter what those entailing laws look like (algorithmic or otherwise) and no matter what sort of 'computers' exist in the system (digital, analog, or something else) so long as any computers are 'physically realizable'.

endogenous variables of a law-governed system must be observable if the model is to be tested or calibrated. And the endogenous variables must be known and listed ahead of time for the analyst to write down the equations. Time plays at most a limited causal role in such a system. Ergodic systems 'go everywhere', so that time and history play no role in the system's dynamics. Spin glass models such as Minniti (2004) exhibit non-ergodicity. But all possible states exist in a stable phase space and are not qualitatively different from one another. Time matters in a weak sense, but the possible paths the system can take are all predetermined before the dynamics unfold. At most, as in Statistical Mechanics, the phase space may increase in dimensions, but the observable properties in the new dimensions are pre-given.

The notion of general equilibrium from economics and phase space from physics share many similarities. Both view systems as bounded, where the space of all possible actions or positions can be delineated *a priori*. The assumption in this sort of economics is that actors omnisciently calculate and compare all possible actions, including future ones, while in thermodynamics and statistical mechanics the assumption is that the trajectories – positions and momenta – of particles cannot be accounted for within the phase space except in statistical terms. Both general equilibrium and phase space assume that all future goods or states can be mapped and calculated (Arrow and Debreu, 1954). While general equilibrium theory has of course looked at the 'process' (or temporal factors) through which markets get to equilibrium – uncertainty, tatonnement, search, and learning (for a recent review, see Balasko and Geanakoplos, 2012) – nonetheless the notion of equilibrium remains central and strongly wedded to phase space-like mathematical formalizations.

But in economic evolution the phase space itself changes continually in ways that cannot be prestated. The Turing machine ultimately has yielded the World Wide Web, selling on the Web, Web browsers, and iPads – none of this was prestatable in Turing's time. Because of this continual change in the phase space, time matters in economic systems.[4] For example, the list of traded goods has grown radically over time from zero for our pre-human ancestors, to a small handful at about the time biologically modern man appeared (Marwick, 2003: 78), to the multitudes of the modern global economy. Beinhocker (2007: 9, 456–457) estimates that the Yanomami have about 300 distinct goods, whereas there may be about 10 billion distinct goods for sale in New York City. This multiplicity of goods is important enough to have its own name. The Latin for trade is *cambio*. Thus, we might call the increase in the number of traded goods 'cambiodiversity'. Cambiodiversity is analogous to biodiversity; it is diversity in the things traded. And it is increasing cambiodiversity that has caused an

4 O'Driscoll and Rizzo (1985) propose a 'dynamic conception of time' for economic analysis. This 'real time' is 'causally potent and creative'; it is 'irreversible', and it generates 'unpredictable change' (p. 62).

increase in wealth. Adam Smith (1776) understood this connection when he said, 'It is the great multiplication of the productions of all the different arts, in consequence of the division of labour, which occasions, in a well-governed society, that universal opulence which extends itself to the lowest ranks of the people' (I.1.10). More recently, Hidalgo *et al.* (2007) have produced evidence suggesting that cambiodiversity is correlated with wealth.

The continual multiplication of goods to trade means continual change in the space within which economic dynamics unfold. Recall that we cannot calibrate or estimate our model unless at least some of the endogenous variables are observable. In economics the observables are prices and quantities or aggregates of them. If we are tracking prices and quantities, new goods change the set of variables we are tracking and change, therefore, the phase space. Tracking aggregates does not solve the problem. The arrival of new goods, and new uses for old goods, implies the need to change our aggregation method, which may imply a change in the behavior of our aggregates and, therefore, a change in the system's laws of motion.[5]

There is an evolutionary logic to this multiplication of goods over time. At a given moment humans in an exchange network trade certain goods. Those goods in that network create what Kauffman has called an 'adjacent possible'. Certain things are possible and others not from a given space or state. Powered heavier-than-air flight was not part of the adjacent possible 100,000 years ago or even 150 years ago. By 1900, however, we had relatively light, reliable, and powerful internal combustion engines. It seemed clear to many would-be innovators that such engines could be mounted, somehow, to wings to create a powered flying machine. Thus, powered heavier-than-air flight was part of the adjacent possible for the Wright Brothers. At any moment, the econosphere's adjacent possible contains opportunities for profitable innovations as well as false opportunities that may tempt action. There are many such opportunities, only some of which will be acted on. Once that has happened, the attempted innovations – some successful and others not – become what we want to call 'enabling constraints' that will change the system's adjacent possible, enabling a different set of profit opportunities. Only some of the profit opportunities in the new adjacent possible were present in the old adjacent possible.

There is some tendency for this process to create larger exchange networks, more goods, greater complexity, and greater wealth. The tendency is not an iron law. Institutional changes in ancient Rome, for example, brought about a

5 There is a large literature on aggregation problems in economics. This literature considers the problem of aggregating a given set of values or relationships, neglecting the problem of increases in the set of things to be aggregated. Some notable reviews include Kirman (1992), Cohen and Harcourt (2003), Felipe and Fisher (2003), and Blundell and Stoker (2005). Fisher (1987) says, 'use of such aggregates as "capital", "output", "labour" or "investment" as though the production side of the economy could be treated as a single firm is without sound foundation. This', he concludes dryly, 'has not discouraged macroeconomists from continuing to work in such terms'.

collapse of trading relationship and, eventually, the payment of taxes in kind. Presumably, the number of traded goods shrunk correspondingly. Nevertheless, there is an evolutionary logic behind the general trend toward increased cambiodiversity. Adam Smith (1776) identified several reasons for the growth of cambiodiversity. The division of labor increases the 'quantity of work' (I.1.5) in part because specialization stimulates technological change (I.1.9). Moreover, the process can be self-reinforcing because 'the division of labour is limited by the extent of the market' (I.3). More, and deeply important, can be the emergence of ever new economic opportunities created by an ever-increasing cambiodiversity itself.

Biological evolution shows similar properties. As shown by Gould (1998) and mathematically explained in Longo and Montevil (2012), phenotypic complexity grows over time, with no aim or direction. This growth takes place along random paths, produced, in an unbiased way, by an asymmetric diffusion of bio-mass over complexity. The asymmetry informally corresponds to already-occupied niches, beginning with the original bacteria, as with species that 'reproduce with variation' (the fundamental principle by Darwin). This creates new niches, as we discuss below.

In his meditation on Adam Smith's 'dictum' that 'the division of labor is limited by the extent of the market', Young (1928: 533) noted that the extent of the market is endogenous to the market process. Each refinement in the division of labor increases wealth, which is an increase in the extent of the market allowing a further refinement in the division of labor. (Endogenous technological change is a part of this self-reinforcing process.) Thus, 'Adam Smith's dictum amounts to the theorem that the division of labour depends in large part upon the division of labour'. Far from empty tautology, Young explains, this point shows how economic growth can be self-sustaining.

> Not only new or adventitious elements, coming in from the outside, but elements which are permanent characteristics of the ways in which goods are produced make continuously for change. Every important advance in the organisation of production, regardless of whether it is based upon anything which, in a narrow or technical sense, would be called a new "invention," or involves a fresh application of the fruits of scientific progress to industry, alters the conditions of industrial activity and initiates responses elsewhere in the industrial structure which in turn have a further unsettling effect. Thus change becomes progressive and propagates itself in a cumulative way. The apparatus which economists have built up for the analysis of supply and demand in their relations to prices does not seem to be particularly helpful for the purposes of an inquiry in these broader aspects of increasing returns. (Young, 1928: 533).

Young describes a system in which regime change is continual. Each change in regime is a toothing stone for the next. Each regime change enables the next. This enablement represents a complex mix of interactions between enabling institutions, actors, and entrepreneurs. The overall process of increasing cambiodiversity is similar to the process of increasing biodiversity. Consider two more or less parallel examples.

In biology, the swim bladder is an adaptation giving some fish neutral buoyancy. The bladder, which probably evolved from the lungs of a lungfish, contains air and water in the right mix to produce such buoyancy. Apparently, water got into some lungs producing a sac with air and water that was then poised to become a swim bladder. This ordinary case of evolutionary adaptation brought about a new function in the biosphere, neutral buoyancy, which then changed the process of evolution, giving the system new species of fish with new swim bladders and new proteins. More importantly for our story, this new function and adaptation, created new evolutionary niches for other organisms. A worm or bacterium might evolve to live exclusively in swim bladders. The swim bladder thus changes the future possible evolution of the biosphere. It is not possible to list such biological innovations ahead of time as they result from the superposition of the unpredictable new 'niche' and the variation of a bacterium or worm produced by random changes, possibly at the molecular level (mutations or the like).

Following Darwin's two fundamental principles, reproduction with modification and selection (negative: excluding the incompatible; positive: enabling the compatible), we understand the phenomenon as follows. Random variability is at the core of reproduction; a 'hopeful monster', in Goldschmidt's sense, with a new and *a priori*, 'pathological' bladder, turned out to be compatible with a contingent environment and was thus positively selected. Given the swim bladder's existence, a new adjacent possible empty niche, or opportunity, emerged, and a variant of a worm or a bacterium then became a possible parasite or symbiote.

Plants provide a paradigm for the extended creativity of evolution. Random specific and *interspecific* hybridation continually creates new species. Now, most (or all) species have *specific* fungi or prokaryotes as parasites or (often essential) symbiotes. They are specific as they did not exist before the new plant species. More generally, plants largely influenced animals' evolution; for example, around 140–100 million years ago, the formation and diffusion of angiosperms with their flowers enabled pollinator insects, by forming previously non-existing niches.

In short, new species and new niches enable yet more species and niches. Moreover, this randomly increases the complexity of the ecosystem, increasing both the diversity of the biosphere as well as phenotypic complexity. Most of plants and animals' plasticity is based on genome and epigenetic effects; the behavioral plasticity of humans is almost exclusively due to a huge, neotenic, highly adaptive brain.

Something similar happens in economic evolution, where human brain and history matter crucially. Consider the emergence of BookScan, a Japanese company that scans books and libraries into iPads. The founder, Yusuke Ohki, wanted to reduce the clutter created in his apartment by the 2,000 books of his personal library. He solved the problem by scanning them into his iPad. Ohki realized he had stumbled into a business idea and founded BookScan, which quickly took off and generated competitors in the Tokyo market (Eki and Alpeyev, 2011).[6] The makers of iPad were probably not thinking about crowded Tokyo apartments when they perfected the tablet computer. And yet their innovation unintentionally created an economic niche Ohki was able to enter. Apple's innovation changed the set of economic niches in the econosphere's adjacent possible in very much the way the swim bladder changed the set of biological niches in the biosphere. This transformative effect of the iPad exists in some degree for more or less any economic innovation, just as the argument in Young (1928) suggests. In this sense economic dynamics are 'creative'. At each step, new opportunities, new economic niches, are created in the adjacent possible. Successful innovations are entries into these newly created niches. The process itself continually generates new possibilities. The process itself generates novelty; it is 'creative'. In this sense we may speak of the 'creative dynamics' of the econosphere.

Our emphasis on creative dynamics is an emphasis on emergence. We are suggesting strong parallels between emergence in the biosphere and emergence in the econosphere. We emphasize the emergence of complexity and, especially, novelty. Harper and Lewis (2012) review the variety of meanings 'emergence' has in modern economics. They note the link to complexity, and they note that only some conceptions of emergence, such as those common in evolutionary economics, imply the emergence of novelty. See also the rest of the volume, which they edited, for important 'New perspectives on emergence in economics'.

Positing that the new goods are all somehow 'out there' in a stable, high-dimensional prestatable phase space waiting to be created cannot solve the problem. In this solution, we would model the system as tracing out a relatively low-dimensional path in a very high-dimensional but prestated phase space. The trouble is that we cannot list elements in this imagined high-dimensional phase space. Consider Beinhocker's estimate of about 10^{10} goods in New York today. This number of realized goods is much smaller than the number of possible goods existing in the imagined high-dimensional phase space. And yet to list all of them at the rate of one per second would take 317 years even if we did not stop to rest along the way! Even if we had all the time in the world, or rather much more than that, there is no algorithm that can list all the future economic possibilities, let alone compare them.

To provide an example: consider the uses of a screwdriver. No algorithm can list all possible uses of a screwdriver. One use, for example, is to serve as an

6 Eki and Alpeyev (2011) suggest that BookScan would not have succeeded if the Japanese market for e-books had not been hindered by inappropriate copyright laws. This may be true, but BookScan's entry to the US market through bookscan.us suggests otherwise.

antenna for a short wave radio. This usage we can list today. But to list it in 1850 would have required that one anticipate the emergence of radio transmission. The number of uses of a screwdriver is indefinite and these uses are not orderable. Therefore no effective procedure, or algorithm, can either list all the uses of a screwdriver or, in general, provide a means to find a new use.

Because we cannot prestate the ever-changing and emergent phase space of economic evolution, we have no settled relations by which we can write down the equations of motion of the ever new economically relevant observables and parameters revealed *ex post* by the market process. Nor can we prestate the emergent opportunities of the system as boundary conditions. Thus, we could not integrate the equations of motion even if we could somehow have them.

If the above is true, no laws entail the evolution of the econosphere. And if by 'cause', we mean what gives a differential effect entailed by law, then we can assign no cause in the evolution of the econosphere. In this sense, the economy is not a causal system. The past does not 'cause' the future so much as it enables some futures and disables others. The main reason for this is that, in theories of the inert (classical physics), the default state is inertia and, thus, nothing happens with no causes; while the 'default state' in biological evolution is Darwin's 'reproduction with variation' and, in human history, it may be fair to consider 'activity with variation', as a default state (Longo *et al.*, 2014). Thus, 'enablement' is a key notion in our analysis. Past innovations *enable* future innovations, but do not *cause* them. Even more so: new niches are enabling constraints that enable innovations, which create new niches.

In the strict sense of 'cause' just given, novelty and innovation are uncaused. Other economists have expressed similar notions. Knight (1921: 221) considered 'the possibility that "mind" may in some inscrutable way originate action'. Shackle (1972: 122) also described choice as 'originative'. Mises (1966: 18) took a similar view when explaining the principle of methodological dualism. Hodgson (1993: 219) describes choice as an 'uncaused cause'. If there are no entailing laws, then some events will be less than fully entailed without being, therefore, arbitrary. Shackle (1979: 20) has captured the point well: 'The anarchy of Nature is as fatal as the determinacy of Nature to the notion of choice as the source of history'. Our focus is somewhat different because novel possibilities emerge in the adjacent possible even before they are discovered by (possibly creative) minds. Like Knight, Shackle, Mises, and Hodgson, however, we articulate a carefully delimited sense in which economics must allow for uncaused causes.

Although the economy is not a 'causal system' in our sense, cause and effect still operate in the econosphere, just as they do in biosphere. Darwinian principles let us predict broad patterns such as the emergence of organisms resistant to pesticides and antibiotics. And it can explain particular past events, such as the evolution of the mammalian eye. Similarly, in economics we may be able to predict certain broad patterns and to explain past outcomes. But relatively specific predictions may be out of reach.[7]

Our summary paraphrases Longo *et al.* (2012):

(1) In law-governed systems such as physics, we can prestate the configuration space or *phase space*. Dynamics are geodesics within such prestated phase spaces – at most the dimensions of the phase space may change, as in statistical physics, but the properties of the observables are prestated. That is, the path of each variable, which depends on the paths of all other variables, minimizes some metric in a predefined space.
(2) In economic evolution, the phase space itself changes continually and in ways that cannot be prestated, since the enablement relation allows the formation of new observables.
(3) Because we cannot pre-state the ever-changing phase space of economic evolution, we have no settled relations by which we can write down the equations of motion of the ever new economically relevant observables and parameters revealed *ex post* by the market process. Nor can we prestate the emergent opportunities of the system as boundary conditions. Thus, we could not integrate the equations of motion even if we could somehow have them nor can we write down a well-defined mathematical function describing (determining) the dynamics.
(4) If the above is true, no laws entail the evolution of the econosphere.
(5) If by 'cause' we mean what gives a differential effect entailed by law, then we can assign no cause in the evolution of the econosphere. In this sense, the economy is not a causal system.
(6) The past does not 'cause' the future so much as it *enables* some futures and *disables* others. Thus, 'enablement' is a key notion in our analysis.

We might note that some attempts have been made to frame new or changing observables in 'second-order dynamics', that is dynamics of phase spaces, a very interesting approach to 'viability' (see, for example, Nation *et al.*, 2002). However, while part of the 'first-order' observables serve as parameters of the 'second-order' systems, where they determine the dynamics of second-order observables, the space of the latter is functionally pre-given, in order to allow the mathematical writing of equations and evolution functions.

In Longo *et al.* (2012; also see Longo and Montevil, 2014), the construction of the phase space in mathematical physics is closely examined: it depends on the invariants that are observed in trajectories. Since Boltzmann and Poincaré, these were transformed into a 'background space' for the complete equational determination (typically: momentum, as observable, with respect to position, as parameter; energy, as observable, with respect to time, as parameter). This is exactly the conceptual operation that those authors claim to be unfeasible in

7 A referee notes the similarity here to the idea of 'pattern prediction' found in Hayek (1967: 24) and O'Driscoll and Rizzo (1985: 27, 85–88). The same referee sees a connection to the warning in Hayek (1978: 23–34) against the 'pretense of knowledge'.

biological evolution and that we claim to be unfeasible in economic analysis, since these very observables dynamically change and new unprestatable ones are continually created. When the double jaw of some vertebrates was transformed into the bones of the middle ear of later vertebrates (Gould's preferred example of 'exaptation', adaptation *ex post*), a new unprecedented observable, most probably a consequence of a random molecular or epigenetic event, is formed, around 250 million years ago, and changed the niche and the ecosystem.

> When those arts that proceed from design come into competition and their craftsmen work in rivalry, without doubt the good intellects, exercising themselves with much study, discover new things every day in order to satisfy the various tastes of men (Giorgio Vasari).

3. Novelty intermediation

If economic evolution is 'creative' in the sense we have indicated, then novelty is ubiquitous in economic affairs. Novelty can be squelched by a sufficiently rigid institutional system, such as the Stalinism of the old Soviet system or the manorialism of medieval Europe. But even a squelched system produces some novelty as illustrated by Sputnik or the flying buttress.[8] More open systems generally produce more novelty.

We are, of course, not the first scholars to note that economic systems generate novelty. Adam Smith (1776) attributes the greater productivity of the division of labor in part 'to the invention of a great number of machines which facilitate and abridge labour, and enable one man to do the work of many'. He notes that 'the invention of all those machines by which labour is so much facilitated and abridged, seems to have been originally owing to the division of labour'. He further notes the emergence of 'philosophers or men of speculation, whose trade it is not to do any thing, but to observe every thing; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects'. In this passage Smith adopts the theory that creativity is recombination. Campbell (1960) and Koestler (1956) are frequently cited examples of combinatorial theories of creativity. In his review of 'creativity research', Mumford (2003) emphasizes the importance of 'conceptual combination' in 'creative thought'. Witt (2009) adopts a combinatorial view, describing novelty generation as a process in which 'conceptual inputs . . . are recombined' (Witt, 2009: 371).

The combinatorial view of creativity may raise a puzzle. Why don't we run out of elements to combine? This concern has been expressed in the economics literature. Cowen (2011) argues, for example, that we have reached

8 A long tradition stemming, apparently, from Lefèvre-Pontalis (1920) holds that the first true flying buttresses came with Notre Dame de Paris in about 1180. But James (1992) has found evidence for flying buttresses in the West as early as 1160.

a 'technological plateau', creating 'The Great Stagnation' (location 64).[9] Schumpeter's notion of the 'mechanization of progress' (Schumpeter, 1947: 131) might be another example. Schumpeter imagined that 'capitalist evolution – "progress" – either ceases or becomes completely automatic' (p. 134). A 'completely automatic' process may be 'innovative' in some constrained sense, but it seems fair to say that a mechanized system cannot produce 'true' novelty.

Our argument shows that there is no particular reason to expect potential novelty production to decline as we try out more and more combinations. If the system's dynamics are 'creative' in our sense, then it constantly generates new elements (and new uses of old elements) that might be combined and recombined in novel ways. Thus, even if recombination 'can easily be imagined to be carried out mechanically or by an alpha-numeric algorithm', as Witt (2009: 364) suggests, the elements being 'mechanically' recombined are new and could not be listed algorithmically in advance. Witt makes a further point that there is no algorithm that could describe or replace the 'interpretive operation' that discriminates between combinations 'that do make sense and those that do not'. Thus the problem is not so much the lack of things to be combined, but rather the specification of a mechanism for explaining which of the many elements ought to be combined (Felin and Foss, 2011).

While generally benefiting from novelty, the people in systems with more novelty will have more difficulty coping with it. Following Earl and Potts (2004) and Potts (2012), we should expect to see market mechanisms for coping with novelty. Earl and Potts (2004) discuss the 'market for preferences' and Potts (2012) discusses 'novelty bundling'. In both cases they largely restrict their attention to the phenomenon of businesses helping households to cope with novelty. We will extend their insights to markets more broadly and speak of 'novelty intermediation'. Households, businesses, and states must cope with novelty and may be willing to pay a specialist to help them do so. A novelty intermediary has specialized knowledge about an area in which novelty seems to matter, digital technology for example, and updates that knowledge frequently. This intermediary transfers such knowledge to its clients or otherwise helps them to cope with novelty in the area of its specialization. Most economic theories and models in which novelty matters will anticipate in some degree the notion of novelty intermediation, but Earl and Potts (2004) and Potts (2012) may be the first clear and reasonably complete statements of the basic idea.

Potts (2012: 295) illustrates novelty bundling with 'fashion magazines such as *Vogue*', which present readers will novel combinations of fabrics, clothing items, hair styles, and so on. Earl and Potts (2004: 622) point to 'product

9 Cowen (2011) does not offer a theory of creativity. He nevertheless illustrates the concern that the potential for creativity may peter out. Cowen makes two distinct arguments, without distinguishing them. First, we have run out of new technological possibilities beyond small tweaks to existing systems. Second, badly designed regulation has choked off innovation. We engage only the first argument.

review websites such as Amazon.com'. They note that novelty production creates a 'framing problem', which has been ignored in standard microeconomics. In standard microeconomic theory 'the frame given by preferences and prices is always unambiguous'. But consumers coping with novelty cannot be expected to have a complete set of preferences across all possible bundles of market goods. Some of those goods are new and it is not clear what combinations will best satisfy the consumer's preferences. Analytically, Earl and Potts view 'high-level preferences' as given and known to the consumer. But a 'market for [low-level] preferences' is necessary if the consumer is to translate high-level preferences into a market plan. In the market for preferences experts help consumers negotiate novel products and novel product combinations. They argue that 'the fundamental knowledge problem that an evolving economy poses for boundedly rational consumers is solved to a significant degree by specialized learning rather than by individuals learning in a self-contained manner across the whole compass of their lives' (p. 631).

Novelty intermediation is not about the diffusion of innovations. It is about finding the innovation in the first place. In our model of creative dynamics, novel possibilities emerge in the adjacent possible. Novelty intermediaries know how to discover the new knowledge required to innovate. There is a structure to the intermediary's knowledge of some changing field and this structure of knowledge allows it to discover the novel possibilities of the adjacent possible, including novel combinations of elements, some of which may be old and others, perhaps, new. It is not correct to equate this discovery process with the diffusion of innovations because it is about discovering the innovation rather than either adopting the innovation or the rate at which a given innovation spreads. Nor does novelty intermediation deal with the emergence of novel possibilities in the adjacent possible. It deals with process of discovering such possibles and turning them into actuals.

Firms and governments are no less in need of novelty intermediation than consumers. It seems reasonable to guess that if economists more fully absorb the ideas of novelty production and creative dynamics they might see familiar phenomena in the new light of novelty intermediation. From this perspective we might begin to reconsider, for example, the role of venture capital (VC) in rapidly changing industries. Using data on European firms in 'medium and high-tech manufacturing and services industries' Croce *et al.* (2013: 495, 503) produce evidence that 'non-financial value added provided by VCs' is 'the main driver of the better performance of VC-backed firms'. We may conjecture that the 'non-financial value added' is often novelty intermediation, at least when the VC firm specializes in a rapidly changing industry. The VC may be bringing more than capital and general expertise to the startups. They may be guiding the startups through the novel possibilities of the industry's adjacent possible.

Presumably, VC firms in Silicon Valley have been providing novelty-intermediation services to startups. The description given by Florida and Kenney

(1988: 311) seems to support that view. 'Between 1968 and 1975', they report, 'approximately 30 new or reconstituted venture capital operations were established in the Bay Area'. This period saw 'the emergence of the limited partnership' VC firm 'with professional venture capitalists managing capital provided by passive outside investors'. Importantly, 'Over time, a growing group of former entrepreneurs, past employees of venture firms, and outside personnel were able to attract financial resources and launch limited partnerships'. The emergence of VC partnerships that included former entrepreneurs seems to be evidence that such firms were acting as novelty intermediaries.

Renaissance art patronage might also be reconsidered in the context of novelty intermediation. Nelson and Zeckhauser (2008) take it for granted that the artists are the experts hired by the patrons who are not experts. But they also point out that some patrons were well informed and had good judgment. We suggest viewing patrons as novelty intermediaries providing a 'non-financial value added' to artists. Patrons were 'combining together the powers of the most distant and dissimilar objects' by simply associating certain artists with one another. Gilbert (1998: 395, 396, 398, 405, 436) notes that humanist experts might give artists advice or instruction on iconography and symbolism. In some cases patrons provided such expert advisors (see Gilbert, 1998: 395, 396, 405). Krautheimer and Krautheimer-Hess (1956: 171) say 'calling upon' a 'scholar to submit a learned program' for a commissioned work was 'established custom'.[10]

According to Hollingsworth (1994), 'One of the most forceful myths of the Renaissance is the idea that its artists freely explored their ideas and created their masterpieces for enlightened patrons eager to acquire these works of genius'. Rather, 'it was the patron who was the real initiator of the architecture, sculpture, and painting of the period'. The patron 'played a significant part in determining both form and content. Fifteenth-century patrons were not passive connoisseurs: they were active consumers'. In a remark significant for us, Hollingsworth says, 'It was the patron, and not the artist, who was seen by his contemporaries as the creator of his project and this gave him the strongest possible motive for controlling its final appearance' (p. 1, 2). At the time, patrons were recognized as creative actors in the arts. Hollingsworth's model of the active patron strengthens the view that patrons may often have been acting as novelty intermediaries and experts in the adjacent possible of relevant areas.

Mateer (2000: ix, x) reinforces Hollingsworth's model of Renaissance patronage. It is 'demonstrably a romantic myth' that 'artists worked in an atmosphere of creative and intellectual freedom, producing masterpieces that were received passively by enlightened patrons'. This romantic view is inconsistent with 'the hierarchical structures of a typical Renaissance court' in which 'every aspect' of life 'was designed as a manifestation of its "prince" and an embodiment of his, or her, values'. The princely patron 'would naturally pay

10 Gilbert (1998) objects, however, that, 'he cites no prior cases, nor is any known to me' (p. 395).

close attention to the development of any commissioned work and expect to participate in the creative process as an active collaborator' (p. ix).

As discussed by Flap (1990), patronage itself might be seen as an 'institution in its own right'. Thus the whole system of interaction between artists, entrepreneurs, and patrons represents far more than just a simple exchange relationship, but rather a complex institution that enabled the generation of novelty.

Long (1997: 3) emphasizes the political and, especially, military functions of patronage. She says, 'in the fifteenth century the practice and representation of rulership came to be closely associated in particular ways with technological power and the mechanical arts'. At that time, Long explains, 'Rulers, princes, and military captains who wanted to consolidate their power achieved legitimation through the remodeling of urban space, the construction and decoration of great palaces, and the creation of painting, sculpture, and other material artifacts' (p. 4). Importantly, the practice of 'military leadership came to be closely associated with armaments and techniques' (p. 5). The successful Italian *condottiero* such as Ludovico Sforza, the Duke of Milan, had to be familiar with the arts and with their corresponding technologies. Long relates a fanciful story from Filarete's *Treatise on Architecture* in which the architect, the lord, and the lord's son are dining together as equals. The lord's son becomes so taken with the architect's knowledge that he pleads with his father to let him study under the architect. Long says, 'He wants to know how metal is melted, [and] how furnaces for melting bronze are made' (p. 33). While fictional, the story strengthens the view that some patrons such as Ludovico Sforza had to have some technical knowledge of the arts, and that they sometimes acted as novelty intermediaries to defend and expand their power, including their military power.

The view that some patrons were producers and novelty intermediaries is bolstered by recognizing, as Long (1997) does, the multiple roles of artisans in the political and military life of an Italian city in the Renaissance. Architecture has an important military function. The brothers Giuliano and Antonio da San Gallo received many commissions for fortifications and war preparations (Vasari, 1568: 696–710). Vasari (1568: 74) recounts the story of how the sculptor Nicola Pisano (1250–1278) found an ingenious method to safely 'throw to the ground many towers' in Florence. The political and military importance of this work of demolition is reflected in Vasari's remark that these towers were important in the many 'brawls that were often taking place between the Guelphs and the Ghibellines' at the time (p. 74). Leonardo's war machines are well known. He may have been the inventor of the wheel lock system of firearms ignition (Foley *et al.*, 1983). Whether Leonardo's designs for war machines were unoriginal, as Gille (1966) suggests, or innovative, as Foley *et al.* (1983) suggest, it remains true that 'Leonardo labored on military devices for Ludovico Sforza' (Foley *et al.*, 1983: 399).

Gilbert (1998: 392) opposes the view that 'Renaissance patrons usually kept creative control over works they commissioned'. But if patrons were novelty intermediaries, then they would be collaborating with the artists and not giving them orders. As Gilbert (1998: 397) notes, Sassetta's 1439 contract for the altarpiece of the church of San Francesco in Borgo San Sepolcro includes the stipulation that the artist will compose and arrange the figures and stories of the work 'as seems fitting to us and the master together, etc' (Banker, 1991: 54).[11] This passage reinforces the view of patrons as collaborators who would likely have, as Gilbert (1998) documents, varying degrees of involvement and control depending on such varied considerations as the patron's knowledge, the purpose of the work, and the artist's stature.

Vasari's (1568: 465) description of Francesco di Giorgio Martini (1439–1502) is revealing.

> Francesco was a very able engineer, particularly in connection with military engines, as he showed in a frieze that he painted with his own hand in the said palace at Urbino, which is all full of rare things of that kind for the purposes of war. He also filled some books with designs of such instruments; and the Lord Duke Cosimo de'Medici has the best of these among his greatest treasures. The same man was so zealous a student of the warlike machines and instruments of the ancients, and spent so much time in investigating the plans of the ancient amphitheatres and other things of that kind, that he was thereby prevented from giving equal attention to sculpture; but these studies brought him and still bring him no less honor than sculpture could have gained for him. For all these reasons he was so dear to the said Duke Federigo, whose portrait he made both on medals and in painting, that when he returned to his native city of Siena he found his honors were equal to his profits.

Notice that Francesco's military knowledge, like his knowledge of sculpture, was linked to 'the ancients' and the study of their achievements. Vasari does not clearly distinguish between the sort of things we might now label 'engineering' or 'technology' and what we might now think of as 'high art' or 'pure art'. The 'painters, sculptors, and architects' were united in their practice of 'design' (*disegno*), which meant, at root, drawing. The person who could draw, could design a beautiful fresco, decorations for a public festival, a new bridge for commercial traffic, or war machines. Some patrons added value to the artists they sponsored through at least three forms of novelty intermediation. First, they had collections of ancient artifacts to which these artists gained access. Second, such patrons brought together complementary artisans who could learn from and emulate one another. Third, they brought humanists and artisans into collaboration. The efforts of these artists, in turn, added value to the political projects of such patrons, including war making.

11 'Per commissionem di frati, del Guardiano et deli operieri de'convento del Borgo laquale è data a noi frate Fancescho et frate Michelagnilo de ordinare et componere le figure et l'istorie della taule sì como pare a noi et al maestro insieme etc'.

Vasari tells a famous story about Giotto that illustrates our suggestion that patrons were sometimes innovation intermediaries. According to Vasari (1568: 102–103), Pope Benedict (the IX), who was planning 'to have some paintings made in S. Peter's', sent one of his 'courtiers' to investigate the renowned artist. When the courtier asked for a sample of Giotto's work, the artist responded by drawing a perfect circle freehand and giving it to the courtier, who was embarrassed by the seeming slight. Upon seeing the drawing and learning that it was done without a compass, the Pope 'recognized by this how much Giotto surpassed in excellence all the other painters of his time' (Vasari, 1568: 103). In this story, the Pope was not interested in the particular design Giotto might have made for the paintings to be commissioned. It seems instead that the artist's general technique was of interest, which suggests the patron's role as producer as well as consumer of artistic innovation. Land (2005) notes the similarity of Vasari's story to two earlier stories told of the ancient artist Apelles. In each of these two stories, however, we have a competition between two artists, and there is no role for a patron. What is significant for us in the story of Giotto's O is the central role of the patron who is interested not in the final product, but in the process of production.[12] Presumably, the story is false. Land says it is 'clearly fiction' (2005: 6). But the role played by the patron in this story does bolster the view that such patrons may have been novelty intermediaries.

The economic theory of professions as developed by Savage (1994) and Langlois and Savage (2001) anticipates the notion of novelty intermediation at least somewhat. Professions such as medicine may exist when the professional must combine expertise based on general principles with judgment based on specific circumstances. 'As a result', Langlois and Savage explain, 'professionals do not standardize the application of their routines . . . but only the "toolkit" of routines from which they draw' (2001: 155). Professions may exist when general knowledge is more or less static. The general principles of the profession will then be embodied in a static set of routines characterizing the profession. Traditional Chinese medicine (TCM) seems to fit this description of a profession with a static knowledge base.[13] If the professional knowledge base is dynamic, Langlois and Savage explain, 'professionals must also employ judgment in the creation of new routines' (2001: 155).

It seems reasonable to guess that many economic phenomena may be subject to reinterpretation as, in part, novelty intermediation in the context of creative dynamics.

12 The first similar story appears in Pliny the Elder's *Natural History* and thus long predates Vasari. The second appears in a 15th-century treatise by Filerete on architecture and thus predates Vasari, but comes after Giotto. It may be that this second story draws on a pre-existing story of Giotto's O. Indeed, Land (2005) notes a reference to Giotto's O that predates Filerete's treatise.

13 Tang *et al.* (2008) say, 'Despite decades of research and integration, the fundamentals of TCM remain largely unchanged and its theories inexplicable to science'. This assessment does not exclude the possibility of future innovations.

> [T]he bold, creative, innovative entrepreneur, too, is at a yet higher level of abstraction also engaged in arbitrage (Israel Kirzner).

4. Toward an entrepreneurial economics

It is not yet clear what an economics for a creative world will look like. We have described a creative world in which the model of explanation borrowed from physics does not apply. Our discussion of creative dynamics suggests that mathematical methods are less powerful than economists have generally imagined in the post-war years.[14] In particular, well beyond the familiar limits of computability, the phase space construction, as practiced in mathematical physics and standard mathematical approaches in economy, does not apply in the econosphere.

Our picture of creative dynamics in the econosphere does not automatically provide the sort of clear policy prescriptions some readers may desire. In particular, it does not allow us to call for 'more regulation' or 'less regulation' of 'the market'. It is, perhaps, a truism that we do not need 'more regulation' or 'less regulation', but 'right regulation'. And yet truisms must not be forgot. Designing wise regulation is a vast topic, given the creation of partially prestatable adjacent possible strategy spaces in the evolving econosphere. Preventing regulation from serving special interests rather than the common good is also a vast topic. We hope and expect that our analysis may inform policy when combined with close institutional analysis and an interpretation of economic history. In other words, facts matter and details matter. The current necessarily rather broad essay cannot enter into the level of factual detail required to produce relatively specific policy recommendations. Our main result is not 'positive' in that sense, but entirely 'negative' in the sense developed by Longo (2008).

Our central result that there can be no entailing laws of economic dynamics is a negative result. We think it would be an error to view negative results as somehow cause for disappointment. Longo (2008) has noted the long-term value of negative results, which destabilize our expectations for 'positive' theory without necessarily indicating where to go from there. Negative results have marked the beginning of new scientific thinking on several occasions. Poincaré's Three Body Theorem, Heisenberg's uncertainty principle, and Gödel's theorem, all opened up new ways of thinking (Longo, 2008). Limits clarify what is feasible and what is not feasible with the existing tools. They may show us new directions by their very nature, at least if the analysis establishing limits has a sufficiently precise scientific content. Negative results, by setting or showing constraints and limits of current knowledge, enable new ideas, new forms of thinking. By the

14 A referee suggests that our analysis may provide a critique of econophysics, which seems right. But probably to properly provide such a critique would require a separate paper.

very methods used, Poincaré's result started the modern Geometry of Dynamical Systems and, later, Chaos Theory. Gödel's 1931 theorems allowed us to define Computability and enabled Proof Theory. It may take time, however, for those new directions to emerge clearly.

Longo (2008) notes that negative results run counter to the 'culture of results' in today's scientific funding agencies. He says,

> The resistance [to negative results] may not only be of a philosophical nature, but may also stem from this "culture of results" more than "of knowledge," a culture which increasingly claims to completely direct science. The accountability obligation, increasingly required by the managers who rule the scientific financing, is of an industrial type and imposes its paradigms: one must beforehand clearly set out the projected methods, the expected results (the "deliverables" . . .) in order to be able, at the end of the project, to compare them with the results effectively obtained.

We cannot be sure where our argument will take us. It seems reasonable to suggest, however, that our discussion points toward an economic theory in which 'entrepreneurs' solve the 'frame problem' of social systems that allow relatively dispersed decision making. We are not aware of any earlier work forging a tight logical link between entrepreneurship and the frame problem. It may be helpful, therefore, to spend some time carefully developing the concept of the frame problem.

In a creative world, the system must adapt to unforeseen and unforeseeable changes that represent new possibilities and new opportunities in the adjacent possible. By definition, no prestated algorithm can anticipate such changes. The system, therefore, must be capable of adaptive, non-algorithmic change. The system must, as it were, continually change its frame of analysis. We may define the *frame problem* as the problem of modifying the system's implicit frame of analysis to adapt successfully to non-algorithmic change in the adjacent possible. Our 'frame problem' is similar to the 'framing problem' of Earl and Potts (2004: 622) noted earlier.

It is true, of course, that the system as such does not make decisions and cannot, therefore, have a 'frame of analysis' in any strict sense. Rather, each decision maker within the system has its own frame of analysis or even multiple frames that it applies in different contexts. Denzau and North (1994) call these frames 'mental models'. At any moment in time, there is an interlocking set of 'mental models' or 'frames' guiding the actions of the several decision makers in society. It is this set that we call 'the system's implicit frame of analysis'. As Denzau and North (1994) note, these 'frames' or 'mental models' may be shared, which may help to justify our decision to call the inter-locking set of frames guiding action a 'frame' as well. Indeed, following Koppl and Langlois (2001) we note that all interactions in society may be construed as Wittgensteinian 'language games'. (see Wittgenstein, 1953). Koppl (2002: 210–211) gives a set-theoretic analysis of the potentially intricate structure of interlocking 'language games' in society. The 'system's implicit frame of analysis' is not only the set of operative 'mental models' but also, in its public aspect, a set of Wittgensteinian language games, which implies some degree of commonality in the frames of interacting decision makers. I cannot sell you an apple for a dollar unless our ideas of 'apple', 'dollar', and 'trade' are more or less the same. Entrepreneurial discovery implies change in the individual entrepreneur's personal frame of analysis. It implies also, however, a change in the public 'language games' the entrepreneur will play with other actors in society and, we may therefore say, change in 'the system's implicit frame of analysis'.

Biological evolution solves the frame problem all the time. For example, swim bladders created the new unprestatable function of neutral buoyancy in the water column as well as a new niche. The problem is solved in market economies too. For example, consider Yusuke Ohki's entrepreneurial invention of a new use, hence new business opportunity, for iPads in the context of small Japanese apartments in which the accumulation of too many books may quickly create crowded living conditions. These actuals are exactly the enabling constraints that created the adjacent possible business opportunity Ohki seized. In doing so, and in finding a new use for the iPad, he solved the frame problem as well.

The term 'frame problem' seems to have been coined by McCarthy and Hayes (1969). The problem in its original sense arose in artificial intelligence. It is the problem of how to code a sequence of actions without re-coding at each such step a complete description of the system's environment. They give the example of a computer that must be told, 'if a person has a telephone he still has it after looking up a number in the telephone book'. According to Shanahan (2009), 'The first significant mention of the frame problem in the philosophical literature was made by Dennett (1978: 125)'. The puzzle according to Dennett, Shanahan explains, 'is how "a cognitive creature . . . with many beliefs about the world" can update those beliefs when it performs an act so that they remain "roughly faithful to the world"'? Our definition is related to both of these uses, but identical to neither.

By definition, an algorithmic system cannot change its frame of analysis. It seems reasonable to suggest, therefore, that systems concentrating decision making in a small number of 'experts' may be less adept at updating their frames than systems distributing decision making across a relatively large number of persons. In the extreme case of a social system with a controller, the controller is responsible for all frame changes. Even if it is able to solicit advice broadly, it is by definition the controller that decides when, whether, and how to change frame. Constraints on the controller's cognition become constraints on the range of frame changes it can consider. If a frame change is chosen, it must then be translated into changes in the states of the system's other agents. Thus, all details of the frame change must pass through the controller and are correspondingly subject to its cognitive constraints.

With more dispersed decision making, by contrast, there may be no one person responsible for the system's overall frame of analysis. While the lack of control may create the possibility of inconsistencies, it may also reduce the epistemic burden of frame changes by distributing them to dispersed autonomous persons.[15] We may use the label 'entrepreneurs' for persons who notice new opportunities available in the adjacent possible. Each innovation, whether successful or not, is an adjustment in the system's implicit frame of analysis. Over time these adjustments may accumulate and become very large frame changes. In this sense we may say that entrepreneurs solve the frame problem for social systems, or at least for systems that allow dispersed decision making. The frame adjustments we are describing are non-algorithmic. Just as we cannot list all uses of a screwdriver, we cannot list all innovations that entrepreneurs will notice and act on over time. And yet entrepreneurs notice them and act on them. Thus, frame change is non-algorithmic at the level of both the individual and the system.

The entrepreneurial agents of distributed human systems are individually non-algorithmic just as the system is non-algorithmic. The system is non-algorithmic because it generates new uses, thence new possibilities that cannot be listed *ex ante,* as it happens in biological evolution and niche creation. Both evolutionary and human agents cannot be mathematically analyzed in a pre-given phase space – even though the math may conveniently be available – as the dynamics of inert bodies have been investigated in physics. *A fortiori*, they are non-algorithmic because they learn and have protensional (preconscious) or intentional (conscious) actions; that is, they make bets on the future and act accordingly. By this, they alter their models of the world to incorporate at least some of the novel possibilities created by the system's evolution. Such learning is necessarily non-algorithmic because what the agent can learn was not listed and not listable *ex ante*. Protensional actions are not algorithmic because they are based on learning and on betting on novelty.[16]

We might note that these future-oriented 'bets' and associated actions are not necessarily random, nor given by an analysis of past experience, but might in fact be informed by the theories, hypotheses, and conjectures that economic agents have about future possibilities (Felin and Zenger, 2009). In other words, economic actors have generative capacities to postulate future states that are not listable *a priori*. This generative capacity points out that humans are scarcely algorithmic input–output machines (though treated as such by some), but have

15 Adam Smith (1776) seems to anticipate an analysis of this sort when he says, 'In the progress of society, philosophy or speculation becomes, like every other employment, the principal or sole trade and occupation of a particular class of citizens. Like every other employment too, it is subdivided into a great number of different branches . . . and this subdivision of employment in philosophy . . . improves dexterity, and saves time. Each individual becomes more expert in his own peculiar branch, more work is done upon the whole, and the quantity of science is considerably increased by it' (I.1.9).

16 Also, computers may be programmed to learn and even to act, but both activities must be pre-programmed, in a somehow pregiven space of possibilities.

unique abilities to bootstrap novelty, even with highly limited or impoverished external inputs (Felin and Foss, 2011). Note that the human construction of communication by semantic laden language, writing, and gestures provides the enabling conditions for future novelty, and leads to what Wilhelm von Humboldt in the early 19th century called the 'infinite use of finite means'. Importantly, this generative capacity extends well beyond the setting of language – language simply providing us a 'window into the mind' – as this generativity provides the foundation for the more general emergence of novelty in social and economic settings. In all, without getting bogged down in the details of this generative capacity, we simply note that its existence highlights the non-algorithmic nature of human activity, economic activity and entrepreneurship being a clear example.

Shackle (1969: 3–13, 47–61, 278–279) contains a penetrating discussion of the 'listing problem' in economics, which is closely related to our analysis: because choice is 'originative', we cannot list all possibilities for choice or, therefore, the future. We might say that non-algorithmic learning is *true* learning. In a creative world, distributed systems and the entrepreneurs in them are both capable of non-algorithmic change and adaptation, by learning and acting in a changing environment. In short, opportunities are yielded by actuals that create enabling constraints yielding adjacent spaces of what is now possible. Successful innovations are discoveries of appropriate non-algorithmic responses to new possibilities.

From whence come opportunities entrepreneurs may notice? From whence the new partially unprestatable adjacent possible opportunities? We are arguing that, in general, opportunities arise from actuals that are the enabling constraints 'creating' the adjacent possible. In this view, the newly emerging opportunities are unprestatable; they emerge non-algorithmically. Even more: we can have no entailing mathematical theory of the emergence of opportunities in the biosphere or economy, since current equational approaches require the predefinition of a phase space. This non-algorithmicity and non-equational determination is a challenge to the construction of a scientific economics in part because it implies that our most cherished modes and models of 'science' do not seem to apply to economic evolution. Moreover, this is so already for evolutionary theories. Our alternative to more traditional models of 'scientific' economics, then, becomes a kind of entrepreneurial economics.

A central task in entrepreneurial economics is to ask what institutions and laws (conceived, perhaps, as webs of enabling constraints that create adjacent possible opportunities) promote favorable entrepreneurial opportunities. In a classic article, Baumol (1990: 893) says,

> [W]hile the total supply of entrepreneurs varies among societies, the productive contribution of the society's entrepreneurial activities varies much more because of their allocation between productive activities such as innovation and largely unproductive activities such as rent seeking or organized crime.

> This allocation is heavily influenced by the relative payoffs society offers to such activities. This implies that policy can influence the allocation of entrepreneurship more effectively than it can influence its supply.

We interpret Baumol's account of productive and unproductive entrepreneurship as a call for institutional analysis. We ask what institutions promote 'favorable' entrepreneurial opportunities. Here are some rather hum-drum examples that may suggest what we have in mind. Productive new-venture entrepreneurship (the founding of new for-profit enterprise) is promoted by transparency, simplicity, and openness in the legal system. Productive political entrepreneurship is promoted by representative democracy with constitutional constraints. In contrast, powerful actors may try to block innovations that threaten their economic position, their rents. In effect, our power structures themselves have become self-sustaining autocatalytic sets, adapting non-algorithmically to regulations to promote their own survival and power. Hence, these constitutional constraints should be designed to limit the power of special interests and prevent the consolidation of power into the hands of an elite. How to achieve this wisely requires careful innovations, including legal innovations. Finally, productive social entrepreneurship is promoted by freedom of association and movement. It is promoted by a democratic and voluntarist system that encourages critical, innovative thinking and adaptive forms of decision making.

Our rather hum-drum examples of how institutions influence the direction of entrepreneurship are meant only to suggest some of the questions that might be asked in an entrepreneurial economics, and what sorts of answers might be given. We do not mean to suggest that we can predict the future of economic theory. As we noted in our introduction, economic theory is characterized by the same creative dynamics we have described for the biosphere and econosphere.

5. Conclusion

We have made some suggestions about the future of economic theory. In particular, we have discussed novelty intermediation and the move toward a more entrepreneurial economics. But we would not pretend to have a complete system of political economy to offer. Indeed, a truly 'complete' system would seem ill suited to a creative world. Our perspective may support a somewhat skeptical attitude toward economic experts. Berger and Luckmann (1966) long ago noted the risk that 'universal experts' may be rigid and willfully obscure. Experts, they note, 'claim ultimate jurisdiction of the stock of knowledge' which is their specialty (p. 117). Knowledge and expertise are fundamental, yet the rate of obsolescence of knowledge in a creative world is high. And, more importantly, the required updating and reframing are probably best performed in decentralized and democratic manner that cannot be readily reconciled with expert claims to epistemic monopoly.

It seems likely that the tools of high theory should continue to evolve in the direction taken by complexity theory. In particular, computability theory seems to give us a set of tools useful in sorting out what is feasible and what not feasible in both theory and policy. Network theory seems well suited to an economics for a creative world. It is an increasingly important area and we need to work out what we can and cannot know about networks. Economic history is clearly important, as is the related idea of close description of institutions. Our description of creative dynamics in the econosphere seems to suggest the importance of institutions and institutional change, which tends to elevate the importance of thick description, economic history, and applied economics relative to the sort of high theory that dominated economics in the post-war period.

Our hints for the future of economic theory all point to a more institutionally rich analysis. The less that abstract theory has to say, the more work will have to be done by close institutional analysis. As we said in the introduction, our analysis is more metatheoretic framework than applied theory. But in any applied theory that fits our framework 'entrepreneurs' (whether new-venture entrepreneurs, political entrepreneurs, or social entrepreneurs) will act in a specific institutional context. As Baumol (1990) emphasized, different institutions will encourage different sorts of entrepreneurial actions. Thus, for our framework to meet empirical reality, the institutional context must be specified. It must be given in sufficient detail to support general claims about the direction of entrepreneurship.

If we live in a creative world, it may be time to reconsider our methods, our theory, and the role of economists in a democratic society. We have made some broad suggestions along these lines without pretending to have an algorithm for any future economics. We do not have all the answers. We will have provided a helpful prolegomena, however, if our arguments help to promote a larger discussion within the economics profession.

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Economics for a creative world: a response to comments

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Abstract.
We reiterate our main contributions: 1) our more careful demonstration of why "mechanistic" models have limited application, 2) our account of novelty as a system-level phenomenon, and 3) our identification of "novelty intermediation" as important to creative economic dynamics. We also address some criticisms. Pavel Pelikan's idea of stochastic causality does not somehow eliminate unprestateable change. We do challenge certain strong notions of universal causation, as Ulrich Witt notes, but such notions are probably best abandoned. Although we do not repudiate mathematical modeling as our paper suggested to John Foster, we may give less scope than Foster to such methods. Finally, we point out the extreme difficulty of implementing the sort of engineering vision Colander articulates.

Those, who are strongly wedded to what I shall call 'the classical theory', will fluctuate, I expect, between a belief that I am quite wrong and a belief that I am saying nothing new. It is for others to determine if either of these or the third alternative is right.
J.M. Keynes

We are honored to receive comments from an extraordinary group of economists, all of whom are working in one way or another beyond the bounds of orthodox economics. The generally positive tone of the comments and the high level of general agreement are striking to us. However, our commenters do have some objections. Colander thinks we are too hard on mainstream economics, while Foster thinks we are too soft. Foster objects that we seemingly reject the use of mathematics in economics entirely, and Witt seems to think our paper veers into a kind of theoretical nihilism. Pelikan thinks that economists "may not know what to do" with our rather high-level generalities. Finally, there is some question of how innovative our argument might be. Although our commenters were generally favorable to our analysis and always kind, we were sometimes reminded of Henry Hazlitt's criticism of Keynes' *General Theory*: "What is original in the book is not true; and what is true is not original" (1983, p.3).

We think that our analysis does make a contribution if it is correct. Before responding to individual comments, we would like to restate what we think our main contributions to have been.

First, our explanation of why "mechanistic" models are generally inappropriate in economics may be more careful and satisfactory than previous efforts. As we tried to indicate in our paper, we use the potentially elastic word "mechanistic" only for models in which the dynamics are represented as "the unfolding of a process fully described, up to a stochastic error term, by a master set of equations or an evolution function." We show that the phase space *is not* stable and *cannot be* stable, which has not quite been done previously as far as we can tell. We noted the similarity of our analysis to Shackle's discussion of the listing problem. But we get unlistability from a close internal critique of physics-based models rather than considerations of the creativity of human decision-making. (See also Felin, Kauffman, Koppl & Longo, 2014.) Strictly speaking, therefore, our discussion is applicable only to modeling strategies that require a stable phase space.

Second, and relatedly, we show how novelty emerges even without *ex nihilo* acts of "creation" by gods or persons. Novelty production occurs at the systems level in our analysis. As far we can tell this path to novelty and unlistability in economics has not been taken before.

Finally, we develop the concept "novelty intermediation." While we have stuck mostly to a metatheoretic framework, our discussion of novelty intermediation was meant to show that our framework matters for applied work. We noted that Potts (2012) and Earl & Potts (2004) gave us "the first clear and reasonably complete statements of the basic idea." Our treatment advances upon theirs, however, because we identify the structural element in the system that makes it possible for novelty intermediaries to emerge. With Potts (2012) and Earl & Potts (2004), the idea is that certain businesses know about recent innovations that have already taken place, whereas the retail consumer does not. These businesses inform the consumer by suggesting certain combinations or offering products that exhibit certain combinations. In our analysis, instead, the intermediary knows what combinations of *inputs* may generate new *discoveries*.

We turn now to some remarks of our individual commenters. Space constraints prevent us from going into some of the issues as deeply as we might otherwise desire.

Pelikan and Witt both question our rather strong claims about causality. Pelikan thinks we neglect "stochastic causality." Witt upbraids us for denying the "principle of causation." It is a bit difficult to address these serious concerns in part because space limitations prevent each author from fully specifying what these terms mean. Thus, we are only too keenly aware of the risk that we might unintentionally misconstrue their arguments. Such a danger is well illustrated by Hodgson's (2004, pp. 57-65) lucid discussion of causality and of "the ambiguous bogeys of mechanism and determinism." Like Bunge (1959), he notes the diversity of meanings that may attach to terms such as "causality" and "determinism." Bunge's (1959) classic also notes the tension between theories such as those of Locke, Berkley, Hume, and Kant, that view "causation as a mental construct, as a purely subjective phenomenon" and is own view that "causation has an ontological status," though one that "raises epistemological problems" (pp. 5-6). In spite of the dangers of miscommunication, we will address the concerns of both Pelikan and Witt.

When Pelikan invokes "stochastic causality" he may have in mind something like the "probabilistic causality" described by Suppes (1970) and Cartwright (2006). In this theory, C "causes" E if the conditional probability of E given C is greater than the conditional probability of E given not-C. This and similar ideas may seem to conflate epistemology and ontology. However that may be, our purposes suggest a very different sort of response. The similar definitions given by Suppes and Cartwright both require us to have "a state description over a 'complete' set of confounding factors" (Cartwright, p. 58). In a footnote, Cartwright says, "The scare quotes are around 'complete' because it is a difficult notion to define." This wise remark suggests why our "reasoning about the non-algorithmic nature of economic change" may not be "significantly weakened" by notions of "stochastic causality." Such notions would seem to depend on a stateable set of possibilities such that a probability measure may be defined. But if our vision of creative dynamics is about right, a probability measure cannot generally be defined unless possible events are described only in very general terms. For similar reasons, we doubt that the notion of "stochastic algorithm" mentioned by Pelikan would much alter our analysis.

We might evade Witt's criticism of our views on "law" and "cause" by pointing out that we have criticized only a very narrowly circumscribed set of ideas on law and cause. Our repudiation of "entailing laws" leads us to reject the notion that the future is somehow wholly contained in the past. We are weaving our way into the future, not unrolling a tapestry that was completed long ago. We are conscious of C. S. Peirce's remark, "The great principle of causation which we are told, it is absolutely impossible not to believe, has been one proposition at one period of history and an entirely disparate one [at] another and is still a third one for the modern physicist. The only thing that has stood . . . is the *name* of it" (1898, p. 197). Witt seems to recognize the issue when he says, "The problem seems to be that the notion of a 'law' can be given different meanings." We explicitly note, as Witt acknowledges, that "cause and effect still operate in the econosphere."

We could dodge Witt's criticism in this way, but we will not. We have indeed taken a swipe at notions to the effect that every thing has a cause, or at least a cause that we can identify in advance. We think it is noteworthy that our position emerges from a careful look at one relatively narrow class of models rather than general considerations of "cause" or "law." In any event, the conclusion that economic change is not algorithmic does compromise at least some notions of the "principle of causation." In this sense it is, perhaps, "radical." We are not alone in chipping away at such notions. Chaitin has interpreted algorithmic information theory to imply that "certain mathematical facts are true for no reason" (2006, pp. 77-78). Citing Bell's inequalities, Filk and von Müller have noted that "Leibniz' principle of sufficient reason does not hold in quantum theory" (2009, p. 64). If we are going to hold fast to strong notions of universal causation, it seems, we will have to ignore or deny some important results in mathematics and physics.

In physics we know what we mean by cause. In classical physics, for example, force is mass times acceleration. In chemistry too we know, at least for classical chemical reaction systems. In quantum mechanics "cause" is less clear. And in evolution it may be even less clear. Certainly, we would all say that the tiger biting the gazelle "causes" its death. But Longo Montévil and Kauffman (2012) deny entailing laws for evolution. If "causal mechanism" and "cause" require *entailing laws*, then there is no causal mechanism for evolution as a whole. In the social sciences, where responsible free will and consciousness may play a role, what should we mean by "cause"? Are preferences (utility functions) "causes"? Beyond that, our claim is that enablement is real. We might say that finding a loophole in a law (as it were) *enables* but does not *cause* the new strategy that may emerge and endure. The mainframe computer's success did not *cause* the personal computer but it did (with the invention of the chip) *enable* the PC whose wide sale did not *cause* but did *enable* the emergence of word processing, and so on to the web and to selling on the web. Each of these innovations was *enabled-but-not-caused* by what had come earlier.

Our biggest disagreement with Foster concerns his characterization of us as "non-economists"! This is perhaps technically true of Kauffman, Felin (more or less), and Longo—at least in terms of their primary training and disciplinary background. But Koppl's graduate training was in economics. Indeed, Koppl is usually considered something of an "Austrian," which might make him a heterodox economist (Koppl 2006). And his previous co-authors have included economists from other heterodox schools. Kauffman and Felin have also respectively contributed to economics: Kauffman to evolutionary economics and Felin to the domain of organizational economics. Space limitations drove us to make only some references to these literatures, but not because we were unaware of them. Furthermore, Foster thinks we are “too quick to dismiss mathematics as a useful tool in understanding economic evolution.” Perhaps. But we did express a favorable disposition to several mathematical tools, including the one Foster seems to like best, namely, mathematical network theory. But part of the problem is that even heterodox economics, including mathematized versions, are often built on a particular brand of theorizing (e.g., Nelson & Winter, 1982) which cannot meaningfully account for the emergence of novelty (Felin and Foss, 2011).

Colander says we are too hard on the mainstream and Foster says we are too soft. Those two very different opinions give us hope that we may have hit the Goldilocks point: neither too hard nor too soft, but just right. Colander says the “reasonable mainstream” already has a “skeptical attitude toward economic experts.” If so, some well-respected names may fall outside the “reasonable mainstream.” For example, Reis (2013) has said, “The central bank may be more effective in technical tasks where ability to incorporate quickly changing knowledge is more important than effort at meeting the goals in a strict mandate” set down by the elected representatives of the people (p. 19). This defense of central bank independence expresses little skepticism of economic experts. Policy prescriptions emerging from some of the network-theoretic literature on financial-market contagion (Acharya 2009; Beale et al. 2011; Caccioli et al. 2011; Gai, Haldane,and Kapadia 2011; Haldane and May 2011; and Yellen 2009, 2011) also seems to reflect a sanguine view of economic expertise. Acharya, for example, says it is “paramount” that banks report their “portfolio compositions” to “the regulator” so that it can compute systemic risk and “determine the collective risk capital charge for each bank” (2009, p. 248). But he does not ask whether this procedure gives too much power to economic experts.

Colander says, “the reasonable mainstream’s commitment to formal scientific methodology requires any theoretical considerations to have all i’s dotted and t’s crossed before these policies become part of the academic discourse.” But at least two Nobel laureates have expressed a very different attitude. Akerlof and Shiller (2009) compare the policymaker to the Cat in the Hat who, they remind us, “tried Plan A, and then Plan B, and then Plan C, and then even Plan D.” We should emulate the Cat, they say, and “go on down the alphabet, until we find something” that works (location 263). This zeal to “go on down the alphabet” is hardly the slow and cautious attitude of someone who wants all i’s dotted and t’s crossed. Colander would surely object that he explicitly referred to *science* and not to *policy*, which is always an art (Colander 1992), especially in times of crisis. Yes. But the policy experiments advocated by Akerlof and Shiller seem largely unconstrained by theory, which calls into question the hyper-conservatism of theory Colander describes. The theoretical conservatism of the mainstream (in macroeconomics at least) would not seem to be a point in its favor. The tools of mainstream macroeconomic theory have *not* been evolving in the right direction. The mainstream has been committed to methods that implicitly deny the creativity and dynamism of the real system. It is as if the mainstream is saying that we need to do more work on the theory of ox carts if we are to hope for progress in understanding rocket ships! This hyper-conservatism of macroeconomic theory might be changing in the wake of the crisis, but if so the center of gravity has not yet moved very far.

Finally, we would like to address Colander's important remarks about engineering. Colander has long emphasized the lost art of economics (Colander 1992). Economists have lost sight of the art of economics as understood by John Neville Keynes. Beside the "positive *science of political economy* which is concerned purely with what is" and the "*ethics of political economy*," which "seeks to determine *economic ideals*," there is the "*art of political economy*, which seeks to formulate *economic precepts*" (Keynes 1917, p. 36). These "precepts" are "rules" or "maxims" through which "given ends may best be obtained" (Keynes, 1917, p. 32). This "art" is what Colander has in mind when he tells us to think of applied economics as engineering.

It seems hard to question the desirability of adopting "the strategy for causing the best change in a poorly understood or uncertain situation." But what is that strategy? On this vital question, we do not agree amongst ourselves. Should we support the approach of "complex engineered systems" in which "performance characteristics emerge from the implemented system rather than existing in a fully specified form ex ante" (Koppl et al. 2010)? Or is a more urgent collective response is required, as Longo believes, particularly considering the damage humans may be doing to the ecosystem? Perhaps activities such as the production of new chemicals that might present dangers such as endrocrine disruption (a major challenge now) require the dynamic proposal of rules forbidding this, directing that, and canalizing the other. Perhaps the engineering challenge is how to make economic projects in a continually changing frame.

Whether "the answer" is something about markets, something about democracy, or something else, our vision of creative dynamics shows how hard Colander's engineering task is. It shows how hard it is to know what is "the strategy for causing the best change." To have a *best* strategy, you need a partial order with a maximum and, therefore, some sort of pregiven space, which is exactly what we deny. Our analysis challenges strong notions of optimality in economics and (following Longo, Montévil, and Kauffman 2012) biology. The front legs of a kangaroo, elephant, or opossum are not optimal. They are the outcome of the one possible evolutionary trajectory for tetrapod front legs that happened to have been followed so far. Individuals and organizations may have preferences, which may imply a kind of optimality of individual choices. One may try, as it were, to become a kangaroo, though it may not work. But notions of optimality do not easily apply to the creative dynamics of the biosphere and the econosphere.

Giuseppe Longo's answers, only in part integrated in the published common text.

I will elaborate on some of Colander's comments, *in italics* :

p. 5
Koen defines the engineering method as "the strategy for causing the best change in a poorly understood or uncertain situation within the available resources

Heuristics includes all theories and models, and any other aid, such as intuition, experience

Using an engineering methodology, nothing is off the table.

A scientific methodology is focused on understanding for the sake of understanding

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The distinction science/engineering is surely not new, but it is nicely spelled out here and in a very pertinent way. In particular, it is pertinent as we borrow ideas from biology, evolution mainly. Now, Darwin's theory proposes historical knowledge and in no way it was meant nor it is meant for prediction and action: it is understanding for the sake of understanding.

However, knwoledge of evolution shaped all of biology and reached medicine. Moreover, we have a problem today: our relation to the ecosystem. Some of the effects of human action have an evolutionary relevance. I will mention a major one (endocrine disruptors and cancer) also because I will further elaborate on it on the grounds of our perspective on "creative economics" (the further problem, in my opinion is "which creation do we need to enable, besides new industrial and financial products, besides cambiodiversity?").

In the XXth century we produced 80,000 new (artificial) molecules. The process was accelerated after WWII, as it gradually became possible to apply, at the industrial level, a fantastic achievement of Quantum Mechanics: a deep or almost complete understanding of chemical interactions. So, it has become possible to create new molecules almost at leisure and very often these provided new (sometimes fantastic) material. Theoretical Chemistry, with its formal rules of molecular interaction, followed with delay this fast process and there was an even slower follow up by quantitative and qualitative analyses of the chemical structure vs. activity relationship (see C. D. Selassie, *History of Quantitative Structure-Activity Relationships*, **Burger's Medicinal Chemistry and Drug Discovery,** Sixth Edition, Volume 1: Drug Discovery Edited by Donald J. Abraham John Wiley & Sons, 2003).

As a consequence, we created, with little control and global scientific knowledge, major endocrine disruptors. A recent strong statement on the connection between the endocrine disruptions we witness and (finite combination of) the new molecules we threw in the ecosystem is in E. Diamanti-Kandarakis et al**.** *Endocrine-disrupting chemicals: an Endocrine Society scientific statement.* **Endocr Rev** 30:293-342, 2009. An example, resulting from this increasing cambiodiversity have been the halving of spermatozoa density in western men in 60 years (!!) as well as the increasing incidence of cancer in any life age, in spite of major fights against other specific causes – artificial colors in food, smoke (see A. Soto, C. Sonnenschein. *Environmental causes of cancer: endocrine disruptors as carcinogens.* **Nat Rev Endocrinol.** 6:363-370, 2010). Endocrine disruptors may have an evolutionary relevance: they are deeply affecting our species and many other forms of life.

So, even the purely historical analysis of species' evolution needs today to be transformed also into an "engineering" of our relation to the ecosystem. We need a project, that is a choice on how do we want to live in this or that context, we need to borrow tools from any discipline and combine inventions of techniques with the invention of *rules* on how to handle them.

Like engineers, in economy, as Colander rightly says, we need a project, in particular an economic project. Yet this project cannot be given in a predefined phase space, this is our central theme. First we clearly reject any idea of economy as an equilibrium system and in no way we consider the various equilibrium approaches as scientific, in economy (and biology). It would be like analyzing a Benard cell or a hurricane by extremizing a lagrangian function in an hamiltonian equilibrium context: it is simply wrong. No ecosystem, biological, human, is at (thermodynamic) equilibrium; most of the time, they are not even stationary (constant flow of energy or matter). Nor the "new" approaches to economy, based on statistical physics, escape this judgment. At best they suppose a thermodynamics tending to equilibrium, based on (often implicit) maximum entropy principles; this implies a characterization of the ensemble of micro-states within a given theoretical frame, that is pre-defined phase space and transformations on it.

Finally, we consider inadequate also the very rare far from equilibrium analyses. In physics, also these systems are "state determined", that is history does not matter, only the instantaneous state "determines" the future, even in Quantum Mechanics, where the structure of determination includes randomness (Schroedinger's equation determines the dynamics a probability law, in a pre-given phase space, a Hilbert space – but the treatment, in this frame, is "at equilibrium" as the equation is derivable from an hamiltonian). Biological and human contexts instead are heavily depending on history. In humans, the historical path followed to reach a state of affairs is part of common memory, it contributes explicitly to action and forecast (see G. Longo, *How Future Depends on Past Histories in Systems of Life,* donwloadable, in print, 2015)

Moreover, in our paper, we recalled the peculiar role of randomness in biology, which independently appears in many levels of organization and determination (molecular, cellular, tissue, organismal…) and in their interactions (bio-resonance). Following, Longo and Montévil, 2014, we see randomness as a key contribution to adaptation and diversity, thus to stability, via the notion of "extended critical transition", that is the permanent reconstruction of biological coherence structures in ever changing phase spaces. Similarly, we believe that randomness contributes, in economy, to the creation of new phase spaces, that is the very space of observables and parameters.

This is in radical contrast with existing physical theories and their applications and variants in economy, as randomness is always mathematically analyzed within a pre-defined space of possibilities, or phase space. Out analysis moves randomness up, at the level of the very constitution of the phase space.

Colander's engineering challenge is then: “how to make economic projects in such a continually and changing frame?”. We cannot give this duty up, both for ecosystemic and social reasons. The free creation of new derivative products caused a highly inproductive concentration of richness, similarly as the free creation of new molecules is affecting our biological life. And making human projects means proposing new ways of being together, both as scientific and economic actors; projects refer to the social link and the role of democracy, also in economic (and ecosystemic) decisions. “How can I built this new kind of bridge, which tools, which physical/engineering rules should I follow? Do I need to discover new ones?” asks the engineer. In economy, how can we propose rules that coordinate our human action without killing entrepreneurial, private and public, creativity? We must produce new molecules, but this must be done under a close, scientific follow-up of their ecosystemic consequences; this requires a dynamic proposal of rules forbidding this, directing that, canalizing that other, a major scientific challenge.

In summary, the engineering challenge we are facing in economy is how to contribute to a social environment continually capable of invention as well as to propose rules maintaining an ever changing, but working “coherence” among humans and between humans and their environment. Democracy as the explicit debate on principles is at the core of this process: which is the social agenda in the use of derivative products and tax policies that allowed in the Bush era the transfer of 80% of the growth to 1% of the population? Is this socially and economically viable? How to regulate the fantastic mathematical creativity that accompanied financial market and is now disrupting actual production?

Increasing endocrine disruption and cancer, say, are not viable paths; thus, lists of forbidden carcinogens or biological disruptors, joined to severe control of their industrial production, are not limitations of creativity - as a matter of fact they require major biological understanding and invention. We have to be creative in ruling our human and ecosystemic interactions, by making an explicit, not conservative, but dynamic project, capable of regulating while promoting new viable paths. The fundamental “engineering” challenge is then the creation of viable, motivated, explicitly discussed (an essential component of democracy), dynamically changing institutional regulations, even in absence of a pre-given space of possibilities. A fundamental regulation of our societies also derives from the free social debate, including the right to strike. The disappearance of strikes in the private sectors in euro-countries is a dramatic change; it the loss of a major form of democratic control as well as of a pressure towards industrial novelty creation that had a major role since the end of the XIXth centuries, in spite of the abuses.

In summary, a regulated, yet changing, viable, coherence, as a democratic project, between humans and within their environment is the invention we have to face: inventing working regulations is the hardest but essential creativity which is now more than ever required.

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