

Dosi, Giovanni; Virgillito, Maria Enrica

Working Paper

In order to stand up you must keep cycling: Change and coordination in complex evolving economies

LEM Working Paper Series, No. 2016/39

Provided in Cooperation with:

Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies

Suggested Citation: Dosi, Giovanni; Virgillito, Maria Enrica (2016) : In order to stand up you must keep cycling: Change and coordination in complex evolving economies, LEM Working Paper Series, No. 2016/39, Scuola Superiore Sant'Anna, Laboratory of Economics and Management (LEM), Pisa

This Version is available at:

<https://hdl.handle.net/10419/174548>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

INSTITUTE
OF ECONOMICS



Scuola Superiore
Sant'Anna

LEM | Laboratory of Economics and Management

Institute of Economics
Scuola Superiore Sant'Anna

Piazza Martiri della Libertà, 33 - 56127 Pisa, Italy
ph. +39 050 88.33.43
institute.economics@sssup.it

LEM

WORKING PAPER SERIES

**In order to stand up you must keep
cycling: change and coordination in
complex evolving economies**

Giovanni Dosi °
Maria Enrica Virgillito °

° Institute of Economics, Scuola Superiore Sant'Anna, Pisa, Italy

2016/39

November 2016

ISSN(ONLINE) 2284-0400

In order to stand up you must keep cycling: change and coordination in complex evolving economies

G. Dosi*¹ and M. E. Virgillito^{†1}

¹*Scuola Superiore Sant'Anna*

Abstract

In this work we discuss the main building blocks, achievements and challenges of an evolutionary interpretation of the relation between mechanisms of coordination and drivers of change in modern economies, seen as *complex evolving systems*. It is an evident stylised fact of modern economic systems that there are forces at work which keep them *together* and make them grow despite rapid and profound *modifications* of their industrial structures, social relations, techniques of production, patterns of consumption. We suggest that a fruitful interpretation of the two processes rests in what we call the “bicycle conjecture”: *in order to stand up you must keep cycling*. However, changes and transformation are by nature “disequilibrating” forces. Thus there must be other factors which maintain relatively ordered configurations of the system and allow a broad consistency between the conditions of material reproduction (including income distributions, accumulation, available techniques) and the thread of social relations.

Acknowledgements

This work draws significantly upon Dosi, (1984), Dosi and Winter, (2002), Dosi, (2012) and Dosi and Virgillito, (2016). We gratefully acknowledge the participants and the organizers of the workshop “Explaining Change” held at the Academia dei Lincei, November 2014 and the support by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 649186 - ISIGrowth.

Keywords

Change, Coordination, Evolutionary Economics, Socio-Economic Systems

JEL Classification

O1, O3, P1

*Corresponding author: Institute of Economics, Scuola Superiore Sant’Anna, Piazza Martiri della Libertà’ 33, I-56127, Pisa (Italy). E-mail address: gdoi@sssup.it

[†]Institute of Economics, Scuola Superiore Sant’Anna, Piazza Martiri della Libertà’ 33, I-56127, Pisa (Italy). E-mail address: m.virgillito@sssup.it

1 Change and Coordination: an Introduction

In this work we discuss the main building blocks, achievements and challenges of an evolutionary interpretation of the relation between mechanisms of coordination and drivers of change in economies seen as complex evolving systems. Certainly, in economic systems there are forces at work which keep them *together* and make them grow in relatively ordered manners (often but not always) despite rapid and profound *modifications* of their industrial structures, social relations, techniques of production, patterns of consumption, which as such, are “disequilibrating” forces. Thus, there must be factors which maintain relatively ordered configurations of the system and allow a broad consistency between the conditions of material reproduction (including income distributions, accumulation, available techniques) and the thread of social relations.

Very daringly, indeed, the article attempts to address the two basic questions at the core of the whole economic discipline since its inception which regard, first, the drivers and patterns of change of the capitalist machine of production and innovation and, second, the mechanisms of coordination among a multitude of self-seeking economic agents often characterized by conflicting interests. Of course, of crucial importance are the answers which diverse theories offer to these two questions, but equally important, the relations purported between the two.

The interplay between change and coordination, well before Evolutionary Economics, has been at the core of the analyses of Adam Smith and later Marx and Schumpeter. Change and transformation of technologies, industrial structures, organizations and social relations shape the evolution of the capitalist system which is characterised by processes of endogenous self-sustained growth, punctuated by small and big crises. The process of economic growth is all *but* steady:

Industrial mutation – if I may use the biological term – that incessantly revolutionises the economic structure from within, incessantly destroying the old one, incessantly creating a new one. This process of Creative Destruction is the essential fact about capitalism. [Schumpeter, (1947), p. 83]

Interestingly, Adam Smith begins his *Wealth of Nations* with a detailed analysis of the drivers of change - in particular the positive feedbacks between division of labour, mechanisation, productivity growth and demand growth, while issues of coordination are discussed much later, building on such a dynamic background. Much later and from a quite different angle, Keynes too never dreamt of separating “what keeps the system together” from “what keeps it going”: in fact, the properties of shorter term coordination were derived from the properties of capital accumulation and the animal spirits driving it.

As well known, the current dominant theoretical creed is very much on the analytical opposite to Smith and Keynes. It builds on the separation between “coordination” and “dynamics”, starting from the former, and assuming away the latter in a first approximation. The “coordination research program”, soon culminated into the Arrow-Debreu-McKenzie General Equilibrium model, has been indeed an

elegant and institutionally very parsimonious demonstration of the possibility of equilibrium coordination amongst decentralized agents. However, subsequent basically negative, results have shown the general impossibility of moving from existence theorems to that sort of implicit dynamics captured by proofs of global or local stability - loosely speaking, the property of the system, when scrambled, to get back to its equilibrium state. Quite the contrary, even empirically far-fetched processes such as tâtonnements (with the omniscient Walrasian auctioneer proclaiming equilibrium transaction when he sees them) in general do not converge. Even more powerfully, some of the founding fathers of GE themselves have shown that existence does not bear any implication in terms of the shape of excess demand functions (this is what the Sonnenschein-Mantel-Debreu theorem implies). Putting it shortly, in general even forget local stability! Conversely, any careful look at the toll requirements which sheer existence entails - in terms of information and rationality - highlights the extent to which GE is a beautiful but extremely fragile creature, certainly unable to withhold the weight of any account of the coordination processes of the economy as a whole and even less so, to offer any serious micro-foundation to transforming economies undergoing various forms of innovation. In fact, if the conditions - in term of rationality, characteristics of the exchange, etc. - required in reality were even vaguely as stringent as those required in GE models, probably no one would be ever observed in the real world!

Here, we propose to revert to the old Smithian style of interpretation, beginning with the understanding of the drivers of change and only next try to understand the (imperfect) coordinating properties of the economic systems. It is what we call the *bicycle conjecture: in order to stand up you must keep cycling*. However, in order to operationalize the conjecture, very tall tasks concern, first, the identification of “what is there to be explained” - that is the empirical and historical stylized facts at different level of aggregation and different time scales - and, second, explore how we theoretically account for them.

In contemporary economies one observes that technological knowledge is to a good extent incorporated into corporate organizations, in the form of shared cognitive frames and organizational routines, evolving over time as a result of learning, innovation and adaptation. In turn, such (heterogeneous) firms operate in competitive environments which contribute to determine their revealed performances - in terms of growth, profitability and survival probabilities - and collectively the evolution of the whole industry to which they belong. Indeed, the evolution of diverse industries and the emergence driven by technological and organizational learning are also at the heart of the process of development and macroeconomic growth.

How does the theory accounts for the foregoing historical patterns and stylised facts? Under the prevailing paradigm, it does that trying to rationalise each empirical regularity with “the combined assumptions of maximazing behaviour, market equilibrium and stable preferences, used relentlessly and consistently” (Becker, 1976). Here, we propose an alternative view largely based on opposite building blocks, aimed at understanding the economy as a *complex evolving system*. In a nutshell, such a perspective attempts to understand a wide set of economic phenomena - ranging from microeconomic behaviours to the features of industrial structures

and dynamics, all the way to the properties of aggregate growth and development - as outcomes of far-from-equilibrium interactions among heterogeneous agents, characterized by endogenous preferences, most often boundedly rational but always capable of learning, adapting and innovating with respect to their understandings of the world in which they operate, the technologies they master, their organizational forms and their behavioural repertoires.

In the sections we shall discuss the building blocks of such a perspective (Section 2), some of its domain of applications (Section 3), concluding with some challenges ahead (Section 4).¹

2 The economy as a complex evolving system

Start with the most minimalist notion of complexity: it stands at the very least for the fact that the economy is composed by multiple interacting actors. As H. Simon, also cited in Kirman, (2016), puts it:

Roughly by a complex system I mean one made up of a large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts, not in an ultimate metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole. [Simon, (1969), p. 267]

Indeed, the properties of the whole are generally *emergent properties*, that is collective properties stemming from the local interaction among multiple agents, which however cannot be attributed to the intentionality of any agents or collection of them (more in Lane, 1993; Nicolis and Prigogine, 1977; Camazine, 2001). Note that complexity and emergence do not prevent at all the search for possible laws of motion of any system, but they do rule out any “antropomorphization” of the interpretation of whatever dynamics, so familiar in contemporary theory. Moreover evolution entails that any assumption of “given the fundamentals” (including technologies and preferences) in most circumstances implies a significant violence to the object of study. Of course for any analysis of a complex and evolving economy one has to go well beyond the Schumpeter/Samuelson separation between coordination and change. The (imperfect) coordinating features of the system are fundamentally shaped by its evolving nature. The relatively orderly properties of capitalist economies derive from its being in motion. This is the relative order of “restless capitalism” (Metcalf, 1998). So for example, prices move roughly in line with the average costs of production which in turn depend on the underlying (technology-specific and sector-specific) rates of process innovation. Demand patterns are shaped by the ensuing prices and, possibly even more importantly, by the trajectories in product innovation. Gross and net labour demand are affected by the double nature of technical progress as a “labour saver” and as a “demand creator”. Among many others, these are all features of imperfect coordination in evolving systems. And so

¹A very enticing and compelling discussion, complementary the present one is in Shaikh, (2012).

are the distributional properties of whatever statistics on economic variables which stem precisely from the fact that the system is changing all the time in its process and product innovations, consumption patterns, organizational forms.

2.1 Routines, Rules of Thumb, Heuristics

The first question one needs to address is: *how do agents behave?* In the tradition of Evolutionary Economics, *routines*, *rules of thumb* and *heuristics* have been the core pillars describing the behaviour of agents. In Cohen et al., (1996), S. Winter provides a conceptual classification of the three latter categories: (i) routines are automated, repetitive and unconscious behaviours which require a high level of information processing (e.g. working in an assembly lines, making airline reservation or bank transactions); (ii) rules of thumb are relatively simple decision rules which require low level of information processing involving some quantitative decisions (e.g. the share of R&D over total sales, the fixed mark-up); (iii) heuristics are guidelines and behavioural orientations adopted to face problem solving which do not provide any ready-to-use solution, but only broad strategies (e.g. in decision making, “Do what we did the last time a similar problem came up”, in bargaining, “Ask always more than what you desire”, in technology, “Make it smaller/Make it faster”).

These three elements are the traits of organizations and they are both (i) problem-solving action patterns and (ii) mechanisms of control and governance inside the organization. The conflicting nature of interests, knowledge, and preferences inside organizations, like firms, is well summarized in March, (1962): rather than maximizing units, firms are better represented in terms of political coalitions. In fact, some regular patterns in the behaviour of firms are typical footprint of organizations acting as political coalition. They include (i) the tolerance of inconsistencies in both goals and decisions over time and inside the organization, (ii) decentralised goals and decisions with loose cross-connections, (iii) slowly shifts over time in response to shifts in the coalition But given the nature of the firm as a political coalition, how can we model its behaviour?

In the recent years, the introduction of the computer and the computer program model to the repertoire of the theorist has changed dramatically the theoretical potential of process description models of conflict systems. Complex process description models of organizational behaviour permit a development of a micro-economic theory of the firm. [March, (1962) p. 674–675]

In tracing the Agenda for Evolutionary Economics, Winter, (2016) emphasizes how the use of the maximization procedure is intrinsically inappropriate to study the behaviour of the firms. March, (1962) shared long ago the same concern:

Generally speaking, profit maximization can be made perfectly meaningful (with some qualifications); but when made meaningful, it usually turns out to be invalid as a description of firm behaviour. [...] With few exceptions, modern observers of actual firm behaviour report persistent

and significant contradictions between firm behaviour and the classical assumptions. [March, (1962) p. 670]

The profit-seeking maximizing behaviour of firms is carefully debunked in Winter, (1964) who points two lines of criticism to the assumption of profit maximization: first, even though it is reasonable to conceive firms as having goals, is not appropriate to assume that the operational goal is profit maximization. Rather, organizations try to *satisfy* some objectives operationally different from profit maximization. Second, in a world characterised by continuous change it is impossible to pursue any profit maximization for the lack of any thorough understanding of the detailed structures of ever-changing worlds.

In his Nobel Memorial Lecture Simon, (1979) stresses how the failure of omniscience are “failures of knowing all of the possible alternatives, uncertainty about exogenous events, and inability to calculate consequences” (p. 502). Results from a vast literature in experimental economics show that:

it is not that people do not go through the calculations that would be required by the subjective expected utility decision – neoclassical thought has never claimed that they did. What has been shown is that they do not even behave *as if* they have carried out those calculations, and that result is a direct refutation of the neoclassical assumptions. [Simon, (1979), p. 507]

There are good reasons why agents in such evolutionary environment adopt robust and rather information-independent *heuristics*. But, what is a heuristic?

[It is] a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods. [Gigerenzer and Gaissmaier, (2011), p. 454]

Note that, heuristics are not “biases” yielding sub-optimal behaviours (as one would gather from Kahneman, 2002, or from the bulk of the behavioural economics), but might be “locally ex-post optimal strategies” that outperform purportedly “rational” choices in *large worlds* characterised by *substantive and procedural uncertainty* (Dosi and Egidi, 1991), as well as drivers of major contagion-fuelled disasters.

A clearcut example of the use of heuristics in trading behaviours is highlighted in finance. As DeMiguel et al., (2009) show, over a sample of seven datasets, the simple $1/N$ rule outperforms the Markov Portfolio strategy in fourteen alternative portfolio specifications. “Rational” allocation strategies yield very high estimation errors in the variance-covariance matrices. In fact, in changing and distributional variant worlds, the simple $1/N$ strategy happens to be much more robust and less error prone.

2.2 Coordination vis - à - vis Equilibrium

The term *Evolutionary* recalls the field of Biology wherein the processes of *mutation* and *selection* among species are at the core of *evolution*. Already in the Marshallian

definition of Economics, the latter was conceived to be much more closer to Biology rather than Mechanical Physics:

The Mecca of the economist lies in economic biology rather than in economic dynamics. But biological conceptions are more complex than those of mechanics; a volume on Foundations must therefore give a relatively large place to mechanical analogies; and frequent use is made of the term "equilibrium," which suggests something of statical analogy. This fact, combined with the predominant attention paid in the present volume to the normal conditions of life in the modern age, has suggested the notion that its central idea is "statical", rather than "dynamical". But in fact it is concerned throughout with the forces that cause movement: and its key-note is that of dynamics, rather than statics. [Marshall, (1890), vol. 1, p. xiv]

Nonetheless, the ultimate goal of the neoclassical economic analysis has been to study market coordination as an equilibrium outcome. Coordination is not an easy task: after all the economic processes are the results of individual decisions making characterised by ex-ante possible inconsistencies. But, economic agents coordinate themselves inside organizations, institutions, societies. Why do we observe such emergence of order (where the meaning of order should be accurately distinguished from the notion of equilibrium)?

As well known, the neoclassical response to the problem of coordination has been my means of *prices*: exchange among decentralised agents, who are pursuing their own utility maximization transactions, lead to the emergence of a market. When demand and supply mutually intersect, equilibrium outcomes (that is a system of prices and quantities) are derived: markets clear after all desired transactions have occurred, so that equilibrium price system is such that nobody desires more than what she obtained after the exchange. Apart from the easy criticism on the realism of this approach, and particularly on the validity of the assumptions of perfect competition and rational expectations, which have also been taken up in the neoclassical analysis itself (taking on board, to varying degrees, imperfect competition and asymmetric information), the processes of interactions and evolution of behaviour have been remarkably neglected.

If dynamics and interactions count, the concept equilibrium ought to be rethought and substituted by the notion of *coordination patterns*. In fact, the usual concern for *equilibrium* does not find much place inside the evolutionary theorizing. Without postulating any ex-ante market clearing condition, necessary to endogenously determine a closed solution for the *unknown variables* (e.g. prices and quantities), evolutionary economic models are meant at understanding the coordination patterns that result out of the interaction of heterogeneous agents. The scholar is not interested in finding any deducted equilibrium solution, but rather in identifying *emergent properties*. According to the seminal contribution by Lane, (1993), emergent properties are:

[...] a feature of a history that (i) can be described in terms of aggregate-level constructs, without reference to the attributes of specific MEs (Mi-

crolevel Entities); (ii) persists for time periods much grater than the time scale appropriate for describing the underling micro-interactions; and (iii) defies explanation by reduction to the superposition of “built-in” micro-properties of the AW [Artificial Worlds]. [Lane, (1993), p. 90-91]

Then, let us suppose to have an artificial world populated by machine-producers who make new capital goods and machine-buyers who order the latter to produce homogeneous good sold to the workers. The dynamics of aggregate output, consumption and investment which typically exhibit sustained long run growth and fluctuations are emergent properties not directly linked to the attributes of the microlevel entities.

The emergent properties are conceived to be meta-stable and not unique nor stable equilibria: whenever attributes at the microlevel are changed also the emergent properties can be fairly different. Additionally, artificial economies are mainly high-dimensional stochastic models, hardly treatable analytically. Then, asymptotic convergence toward a steady-state condition or stability are almost impossible to prove analytically. But, notably the conditions under which ordered patterns or trajectories emerge, are the relevant questions addressed by the analysis.

2.3 Heterogeneity

Heterogeneity is a general feature of complex evolving economies in all domains of observation. It concerns productivity dispersions at all levels of aggregation, organizational forms, personal and functional income distributions.

In turn, these heterogeneous agents interact, although in the standard models there is no sign of such interactions. The absence of any explicit coordination process in the latter models is discussed in Kirman, (1992), in his devastating critique of the representative agent (RA):

Paradoxically, the sort of macroeconomic models which claim to give a picture of economic reality (albeit a simplified picture) have almost no activity which needs such coordination. This is because typically they assume that the choices of all the diverse agents in one sector-consumers for example-can be considered as the choices of one “representative” standard utility maximizing individual whose choices coincide with the aggregate choices of the heterogeneous individuals. [Kirman, (1992), p. 117]

According to Kirman, (1992), the RA apparatus is not simply unrealistic but wrong because not well-suited to study problems of emergence and particularly of lack of coordination like unemployment, income inequality, and in general aggregate demand externalities. Related, intrinsic, theoretical flaws of the representative agent concern (i) the symmetry of behaviour between individual and collective rationality; (ii) the reaction of the RA to policy changes maybe fairly different from the aggregate reaction of the individuals; (iii) the ordered of choices of the RA

may not guarantee the individual preference ranking orders; (vi) whenever one does hypothesis testing, trying to compare the model with the data, the modeller does not know if, in case of rejection, has to reject specifically the RA or some other behavioural hypotheses.

If the objective of the neoclassical modeller is to reach the exact microfoundations, ensured by the optimization procedure performed by the RA, the latter procedure intrinsically contradicts the inner meaning of microfoundation. All in all, a direct consequence of the RA is that the no trade conundrum, according to which no exchange should persistently occur as in equilibrium supply and demand clear, becomes the rule and not the exception. Transactions are only mild turbulences around the equilibrium point.

Results from the General Equilibrium scholars themselves highlighted by the Sonnenschein-Mantel-Debreu theorems show that assumed micro properties, like transitivity of preferences, which if violated could lead to multiplicity of equilibria, are not guaranteed by the aggregation process (unless homothetic utility functions, e.g. satisfaction of the Gorman form of all micro agents) are postulated. The only viable set-up explored in the neoclassical models to overcome the aggregation problem has been reducing the dimensionality from n potentially heterogeneous individuals (at least two in the original General Equilibrium program) *to one*. In this latter case, the excess demand function will obviously satisfy all the regularity conditions required to get uniqueness and stability of the equilibrium.

In an alternative perspective, Kirman, (1992) discusses under which circumstances aggregation among heterogeneous agents is sufficient to have a well behaved aggregate demand function:

Once one allows for different micro-behavior and for the fact that different agents face differing and independent micro-variables then [...] complex aggregate dynamics may arise from simple, [...], individual behavior. [Kirman, (1992) p.127]

Becker, (1962) in the early sixties already emphasized how the law of demand is the result of the change in the opportunities, due to the effects that price changes exert on the budget constraint, and are not related to any decision rules: the negative demand slope is *independent* from the rational or irrational content of the decision rules. A similar theoretical discussion is in Grandmont, (1991), who shows the relatively *unimportance of the maximization of a utility function*, and conversely the relevance of the simple satisfaction of the budget constraint to obtain well-behaved aggregate demand functions. The conditions under which aggregation yields to “well behaved” aggregate demand functions independently of the fine specification of micro behaviours is in Hildenbrand, (1994).

More generally, the interaction among heterogeneous agents, by itself, allows for the emergence of endogenous cycles and fluctuations, *without* the need of external shocks hitting the system (see Dosi et al., 2010 among others).

2.4 Innovation and Growth

The process of economic change as been at the core of the “Grand Evolutionary Project” since the seminal book by Nelson and Winter, (1982). The early growth neoclassical models have been identifying in the so called *Solow residual* or, using the felicitous expression by Abramovitz, (1956), the *measure of our ignorance*, the unaccounted source of economic growth. Rather surprisingly, the early scholars of growth theory decided to shelve the enquiry exactly on the source of economic growth, treating “technological change as a residual neutrino”:

The neutrino is a famous example in physics of a labelling of an error term that proved fruitful. Physicists ultimately found neutrinos, and the properties they turned out to have were consistent with preservation of the basic theory as amended by acknowledgement of the existence of neutrinos. A major portion of the research by economists on processes of economic growth since the late 1950s has been concerned with more accurately identifying and measuring the residual called technical change, and better specifying how phenomena related to technical advance fit into growth theory more generally. The issue in question is the success of this work. [Nelson and Winter, (1982), p. 198]

After the early growth models of exogenous technical change á la Solow, the 1990s saw the flourishing of the so called endogenous growth theory attempting to incorporate inherently Schumpeterian themes into mainstream models. Nonetheless, endogenous growth models do not seem able to account for some elements typically characterizing the processes of innovation and growth.

As one of the early evolutionary models of technological change (Silverberg and Verspagen, 1994) puts it, requirements needed to genuinely model endogenous growth are (i) coexistence of many technologies and techniques of production at any given time period; (ii) no unique production function (coexistence of multiple techniques of production even at the frontier); (iii) dependence of the aggregate rate of technical change on diffusion of innovation, not simply on the instantaneous innovation rate; (iv) if the innovative effort is represented by a stochastic draw from probability distributions, the parameters of the distributions have to be unknown for firms.

In fact, such requirements appropriately map into a series of attributes of technology (see also below): search and discovery of innovation are processes intrinsically characterised by Knighthian uncertainty wherein there is no exact correspondence between ex-ante effort and ex-post performance; there is no convergence toward an optimal capital/labour ratio which defines the unique technique adopted by the users, but rather a constellations of techniques of production are employed by different firms.

Then, in the evolutionary perspective it is the exactly contribution of knowledge, which is transferred into the innovative active, which is “responsible” for the neutrino. And innovation is a very special commodity which is not characterised by *scarcity* and by *diminishing returns*, overturning the old perception of economics as

the science of allocation of scarce resource. If knowledge and innovation become the main determinants of economic growth, then abundance and dynamic increasing returns are the rule and not the exception: worlds with endogenous innovation are ubiquitously characterised by *dynamic increasing returns*. If anything, innovation and knowledge accumulation are precisely the domains where the dismal principles of scarcity and conservation are massively violated: one can systematically get more out of less, while dynamic increasing returns are the general rule.

The known properties of information (its non-rival use, non-perishability, scale-freeness in its application etc.), when taken seriously, imply that the usual General Equilibrium properties can be ruled out. In fact as discussed in Radner and Stiglitz, (1984), it is sufficient to assume nonconvexities in the production function, due e.g. to the fixed cost of acquiring information. Given such nonconvexities, the existence of equilibrium is not guaranteed (see Rothschild and Stiglitz, 1976 and its manual-level acknowledgement in Mas-Colell et al., 1995). Under nonconvex technologies, the supply curve is not equivalent to the marginal cost function and the intersection with the demand curve is not ensured. Arrow, (1996) puts it bluntly:

[c]ompetitive equilibrium is viable only if production possibilities are convex sets, that is do not display increasing return [...] with information constant returns are impossible. [...] The same information [can be] used regardless of the scale of production. Hence there is an extreme form of increasing returns. [Arrow, 1996 p. 647-648]

In fact, the existence of a conventional General Equilibrium is undermined in presence of innovation even neglecting increasing returns properties of innovation itself: see Winter, (1971). In turn, the evolution of increasing returns is likely to display as a norm, divergence in e.g. technological capabilities and incomes.

2.5 History

History and path dependency are at the center stage in evolutionary theorizing. So, for example, in order to understand the process of evolution of a given technology, it is fundamental to understand its historical origin. David, (1985) in his seminal contribution emphasises the importance of the sequence of past events to interpret economics as an evolutionary process:

Cicero demands of historians, first, that we tell true stories. I intend fully to perform my duty on this occasion, by giving you a homely piece of narrative economic history in which “one damn thing follows another”. The main point of the story will become plain enough: it is sometimes not possible to uncover the logic (or illogic) of the world around us except by understanding how it got that way. A path-dependent sequence of economic changes is one of which important influences upon the eventual outcome can be exerted by temporally remote events, including happenings dominated by chance elements rather than systematic forces. Stochastic processes like that do not converge automatically

to a fixed-point distribution of outcomes, and are called non-ergodic. In such circumstances “historical accidents” can neither be ignored, nor neatly quarantined for the purpose of economic analysis; the dynamic process itself takes on an essentially historical character. [David, (1985), p. 332]

It is true that New Economic History has brought neoclassical economics to economic history (Fogel, 1965), but it has done it in our view at an unreasonably high price. Cliometrics, and later, the “New Political Economy” focus on the quantitative assessments of sociological and institutional variables which are often then brought into the estimation of long-run production functions. The price is the general assumption that there is a functionally invariant generating process and an invariant economic rationality applicable from Stone Age tribes to space Age societies.

Freeman and Louçã, (2001) provide an enticing discussion on cliometrics. A series of unsatisfying outputs of this research stream culminated with the description of slavery condition as a rational optimizing behaviour for both parties of the contract: the owners were praised for the superiority of their managerial capabilities and the slaves for the superior quality of black labour. Cliometrics, apart from abruptly importing the *homo economicus*, carried also the notion that sheer randomness could adequately capture historical events: first, some of them are considered as random, exogenous events altering the regular (equilibrium) dynamics; second, historical time series themselves are considered equivalent to a sample from a universe of alternative realizations of the same stochastic process. It is basically an ergodic world where “deep history” does not count.

Landes, (1994) emphasises the inappropriateness of the foregoing research agenda in providing exhaustive explanation of historical phenomena:

I am convinced that the very complexity of large systematic changes requires complex explanation: multiple causes of shifting relative importance, combinative dependency,...temporal dependency. [Landes, (1994), p. 653]

Complex evolving systems are typically non-ergodic, thus displaying path-dependencies: where you go depends on where you come from.

2.6 Institutions

In absence of rational, profit-seeking maximizing agents, what does it shape the behaviour of individuals and organizations? How the relatively ordered patterns above mentioned are able to emerge? Is it all the outcome of self-organization?

We have been emphasizing above how (imperfect) coordination and (relatively) ordered change can be interpreted as phenomena of self-organization among multiple interacting agents. However, such processes are embedded into institutions which shape and constrain behaviors and modes of interaction. They include markets, but even more important, other non-market institutions ranging from families to firms, from unions to universities to public agencies.

In turn, “good-matchings” or “mismatchings” among institutional forms are at the core of well-tuned and fragile phases of capitalism development. This is what has been studied by the (mainly French) Regulation School who identified the so called *Regimes of Regulation* (see Boyer, 1988).

Three main domains of the *Regimes of Regulation* are especially relevant to study the capitalist dynamics, namely: (i) *the accumulation regime* which entails the relations among technological progress, income distribution and aggregate demand, (ii) *the institutional forms* which encompass the wage-labour nexus and nature of the State, (iii) *the mode of regulation* comprises the mechanisms by which the former two domains evolve, develop and interact. The modes of regulation capture the specificities of the process of adjustments in the accumulation patterns and in the coordination among different types of actors. Such dynamics yields phases of “smooth” coordination, mismatches, cycles and crises.

The major question is, then, the coherence and compatibility of a given technical system with a pattern of accumulation, itself defined by a complex set of economic regularities and mechanisms affecting competition, demand, the labour market, credit and state intervention. The major finding is the following: there are several different modes of development and regulation observed in history – there is no single universal mode. [Boyer, (1988) p. 68]

The notion of mode of regulation disposes of the standard static equilibrium. It is made of a set of norms, rules, behaviours collectively consistent entailing some distinctive features: (i) decentralised decisions are taken without the need for each individual or organization to understand the whole system; (ii) it shapes the accumulation regime; (iii) it reproduces a system of social relationships.

The role of the industrial relations, the mechanism of wage determination, the relative power of conflicting classes, the industrial and labour policies are also important elements in shaping the national systems of innovation (Nelson, 1993). Non-market institutions are crucial for the understanding of the process of innovative search and more generally of economic dynamics:

[...] there is a lot more to the institutional structure of modern economies than for-profit firms and markets. Firms and markets do play a role in almost all arenas of economic activity, but in most they share the stage with other institutions. In many sectors firms and markets clearly are the dominant institutions, but in some they play a subsidiary role. National security, education, criminal justice and policing are good examples. Some sectors, like medical care, are extremely “mixed”, and one cannot understand the activity going on in them, or the ways in which their structure, ways of doing things, and performance have evolved, if one pays attention only to firms and markets. [Nelson, (2016), p. 18]

2.7 Methodology: why computer simulation

Given the foregoing interpretation of economic dynamics, the choice of the *right* instruments of analysis is of paramount importance (in the following, we shall just address the modelling domain, even if well aware of the complementarity with statistical and historical analyses). To overcome the straitjacket imposed by the standard tools, we advocate an extensive use of computer simulation, concerning both individual action and system-level interactions.

It would appear, therefore, that a model of process is an essential component in any positive theory of decision making that purports to describe the real world, and that the neoclassical ambition of avoiding the necessity for such a model is unrealizable. [Simon, (1979), p. 507]

The choice of computer simulation models is not by chance: it allows to describe the economic agents as behaving according to *procedural routines*, which are executed under the form of algorithms, wherein sequence of actions and events in discrete time can be explicitly inserted and described, and heterogeneity is explicitly modelled. Simulations, in this respect, are not simply used to mimic but to *test* hypotheses.

By converting empirical evidence about a decision-making process into a computer program, a path is opened both for testing the adequacy of the program mechanisms for explaining the data, and for discovering the key features of the program that account, qualitatively, for the interesting and important characteristics of its behavior. [Simon, (1979), p. 508]

Many criticisms have been addressed to computer simulation models, or as they are nowadays labelled, Agent Based Models, particularly, (i) lack of rigorous in the specification of the behavioural equations; (ii) lack of parameter estimation; and (iii) lack of robustness.

The first critique seems to hold in so far as ABMs are a methodology which leaves room of manoeuvre to the modeller, allowing the choice among different specifications of behavioural rules. Conversely, in the neoclassical models only *one* rule is admissible, the maximizing behaviour. However, the greater discipline of the latter is deceiving. The mainstream modeller is allowed full freedom on the choice of the arguments of the function, the functional form and the constraints, without any *external consistency* check (“do actually agents do that?”).

Conversely, ABMs undertake a thorough *external consistency* check in behavioural rules, modes of interaction and timeline of events, which define the chronological order according to which the procedures are undertaken. Thus, the model is asked to be coherent and as close as possible to empirical data. Only abandoning the deductive-normative approach of the maximization endeavour, the modeller is able to test the validity of behavioural rules and algorithms vis-à-vis empirical results. In particular, the modeller searches for stylised facts or empirical regularities.

The second critique is the lack of parameter estimation. According to Brock, (1999), regularities or scaling laws which are particular widespread in economics are:

[...] ‘unconditional objects’, i.e. they only give properties of stationary distributions, e.g. ‘invariant measures’, and hence cannot say much about the dynamics of the stochastic process which generated them. To put it another way, they have little power to discriminate across broad classes of stochastic processes. [Brock, (1999), p. 410]

But the emergence of these scaling law, even if does not allow to discriminate among alternative stochastic processes all equally able to replicate the same unconditional objects, are useful to identify acceptable and non acceptable theories:

Nevertheless, if a robust scaling law appears in data, this does restrict the acceptable class of conditional predictive distributions somewhat. Hence, I shall argue that scaling law studies can be of use in economic science provided they are handled and interpreted properly [...] scaling laws can help theory formation by provision of discipline on the shape of the ‘invariant measure’ predicted by a candidate theory. [Brock, (1999) p.411]

Brock, (1999) advocates both the analysis of unconditional objects and the estimation of conditional ones. ABMs, we suggest, are the best art-form so far available to undertake both exercises. Such models can be used for both *thought experiments* and also as *laboratories* for policy experiments. Instead of performing the usual methods of causality detection proposed by the toolbox of econometrics, what ABMs allow is to model “artificial” worlds.

When ABMs are implemented, the protocol one follows implies: (i) using unconditional objects to reject theories unable to match statistical regularities, (ii) performing policy experiments which allow to understand the reaction of the system when hit by both external shocks, including policy changes, and, equally important, endogenous technological, organizational ones, and structural changes as well.

The ability to match statistical regularities, and particularly large ensemble of statistical regularities at the micro level, attempts to meet the external consistency criteria mentioned above. In accordance with Brock, (1999), ones does not simply try to find unconditional objects, but to build models able to provide a sound explanation of the statistical regularities at different levels of observation. Not all statistical objects are equivalent litmus tests to accept/reject a theory. Replicating business cycle co-movements is difficult but not too difficult. Obtaining Pareto distributions or similarly skewed ones in whatever measure of micro interacting agents is relatively easy: in fact, they are all likely a signature of complexity as such. Getting the two together is much more difficult, and even more is matching the empirical regularities concerning the relative magnitude of the higher moments of different variables.

Finally, the last critique regards the lack of robustness, according to which the results in ABMs tend to be local and potentially valid only for a small set of the parameter space, with the value of these parameters often not estimated.

Notably, ABMs are nonlinear, high dimensional, complex models wherein, to repeat, inputs strongly differ from outputs. Conversely, standard neoclassical models are linearised models around the steady-state. Hence, the two modelling approaches are poles apart in the “epistemological weight” they attribute to the appropriateness of the underlying assumptions about behaviour and interaction mechanisms vs. purported predicting abilities. In ABMs, the values of the parameters are set as close as possible to empirical data, whenever available, even if admittedly often without any direct estimation of their distributions, as they are not generally available.

On the contrary, neoclassical macroeconomic models like DSGE, being linearised in the neighbourhood of the equilibrium values, tend to exhibit a low ability in generating outputs which are different from the inputs themselves. Here, the epistemological strategy is exactly the opposite. The structural model is assumed to be axiomatically true, and on the ground of such truth, the value of the parameters are calibrated in order to match the empirics, by e.g. minimizing the distance between the series produced by the model and the empirical ones. Following a calibration procedure, the modeller does not perform any testing on the inherent model structure, but simply imputes estimated values of the parameters.

In a nutshell, while standard macroeconomic model focus on *parameter estimations*, ABMs entail a sort of theory corroboration. Whenever a model is able to robustly replicate a number of stylised facts, *without* imposing specific values for the parameters, the mechanisms inside the model itself are reliable explanations of the facts empirically observed.

One open challenge ahead is the comparability between high-dimensional ABMs and low-dimensional aggregate law of motions. Can we get rid of high-dimensionality, both in terms of heterogeneity and in terms of variables and parameter space, and still capture some fundamental dynamics of the system? Or putting it an another way, what are the complementarity, if any, between ABMs and classical non-microfounded model such those in the tradition of Kaldor, (1940); Goodwin, (1951); Pasinetti, (1960)?

3 Domains

These are parts of the building blocks of a “grand evolutionary program” (discussed at greater length in Dosi and Winter, 2002) to put at work with respect to the formalization of four main domain of analyses: (i) technologies; (ii) organizations; (iii) corporate learning, competition and industrial dynamics; and (iv) coordination and growth from the micro to the macroeconomic patterns.

3.1 Technologies

Technological innovation, paraphrasing Landes, (1969), has been and is a central driver of the Unbound Prometheus fuelling economic growth at least since the in-

dustrial revolution. The classics - and in particular Adam Smith - were well aware of it, but for almost two centuries thereafter, not much progress had been made in our understanding of the ways new technical knowledge is generated, and how its impact works through the economy (Karl Marx and Joseph Schumpeter stand out as major exceptions). The importance of technological change reappeared, almost by default, in Robert Solow's growth analysis in the 50's, but it is only over the last half century that one has systematically started looking *inside the blackbox* of technology (Rosenberg, 1982).

Fundamental contributions to such a *de-blackboxing* have come, first, from the analysis of the economic properties of information as such, including, as already mentioned, its non-rivalness; indivisibility; and scale freeness in its use; and the (related) increasing returns property both in its utilization and its accumulation over time. However, second, at least equally fundamental contributions have come from the appreciation of the differences between technological knowledge and sheer information - including its varying degrees of tacitness, its organizational embodiment, the difficulties of inter- and intra-organizational replication, and its crucial dependence upon the characteristics of particular technological bases.

In the opening up of the technological black box, the account of technologies in terms of pieces of knowledge, their combinations, and their changes has to be complemented by a more operational representation of *technology in action*. The conception, design and completion of whatever artefact, generally involves (often very long) sequences of cognitive and physical acts. Hence, it is useful to think of a technology also like a recipe entailing a design for a final product, whenever there is a final physical artefact, together with a set of procedures for achieving it.

A major advancement and contribution in the Economics of Innovation is the notion that each technology needs to be understood as comprising (a) a specific body of knowledge and practice - in the form of processes for achieving particular ends - together with an ensemble of required artifacts, on the input side; and (b) quite often some shared notion of a design of a desired output artefact. These elements, together, can be usefully considered as constituent parts of a *technological paradigm* (Dosi, 1982, 1988). A paradigm embodies an outlook, a definition of the relevant problems to be addressed and the patterns of enquiry in order to address them. It entails specific templates for the solution to ensembles of techno-economic problems based on highly selected principles derived from natural sciences, jointly with specific rules aimed at acquiring related new knowledge. Finally, technological paradigms identify the operative constraints on prevailing best practice, and the problem solving heuristics deemed promising for pushing back those constraints. Moreover, technological paradigms both provide a focus for efforts to advance a technology and channel them along distinct technological trajectories, with advances (made by many different agents) proceeding over significant periods of time in certain relatively invariant directions, in the space of techno-economic characteristics of artefacts and production processes.

The technologies as knowledge and as recipe perspective offers an enormous progress in the understanding of what technological knowledge is all about as compared to the blackboxing entailed by the traditional representation of technology

as $output = f(list\ of\ ingredients)$. Moreover, the recipe perspective offers promising venues also to the formal representation of the dynamics of problem-solving procedures involved in any technological activity, within organizations in particular. In such a procedural view, the orienting focus is not immediately the list of inputs and equipment used to produce, say, a semiconductor of certain properties, but rather it rests in the design of the devices and the procedures used in the transformation of the raw silicon into a microprocessor.

Concerning technological advance, modifications and refinements of procedures and designs are *where the action is*, while changes in input/output relations (the production functions) are in a way the by-product of successful attempts to achieve effective procedures and designs with certain performances, and to change them in the desired directions. Thus, what comes under the heading of production functions of whatever kind, is basically just the ex-post description of what appears in the quantity part of the recipes. Note also that, dynamically, in most cases efforts to change recipes directly entail changes in input characteristics and intensities and, conversely, attempts to substitute one input for another involve changes in production procedures. Symmetrically, attempts to substitute the more expensive inputs - so easy when seen from the angle of some standard production function - often require the painstaking search of new recipes and effective procedures.

Granted that, a question with crucial ramification for any theory of production regards precisely the mappings between procedure-centred and input/output centred representations of technologies. Suppose one has a metric in the input/output space, and one is also able to develop, a (albeit inevitable fuzzy) metric in the high dimensional problem-solving space. Next, how do the latter map into the former?

Issues of the same kind regard the relationship between changes in the recipes, on the one hand, and changes in the relative intensities in the use of the various inputs, on the other. Do small changes in procedures correspond to small changes in input/output relations? And, vice versa, do major technological revolutions affecting the way of doing things imply also major changes in the proportions in which different artefacts and types of labour enter into the recipes for whatever output? That is, basically, what are the relationships between changes in technological procedures and the characteristics of technological trajectories, both in the spaces of product characteristics and of input coefficients?

3.2 Organizations

A good deal of innovations are generated within corporate organizations, while technological and organizational innovations are often intertwined. Thus, it is crucial to progress in the formal exploration of the properties of economic organizations seen as *problem-solving entities*. It is promising to represent them in terms of explicit sequences of activities and procedures nested into specific organizational arrangements prescribing *who send which signal to whom*, and *who does what and in which consequence*.

Notwithstanding promising inroads (see Marengo and Dosi, 2005 and Dosi et al., 2003; Dosi and Marengo, 2015), models still fall short of an explicit formal

account of (i) the emergence and dynamics of organizational routines; (ii) the related role organizational memory; and finally, (iii) the links between organizational architectures, knowledge distribution and performances.

The knowledge of an organization regards, first, its cognitive memory - the structure of beliefs, interpretative frameworks, codes, cultures by which the organization interprets the state of the environment and its own “internal states” (Levitt and March, 1988). Second, organizational knowledge includes routines - comprising standard operating procedures, rules and other patterned actions: call that the operational memory of the organization. Both, cognitive models and operational repertoires are the outcomes of learning processes and thus evolve over time in response to experimentation and feedbacks from the environment. However, they might often bear quite high degrees of inertia and path-dependent reproduction, as in fact, by its nature, organizational memory reproduces over time what an organization has learned throughout its history.

Signals from the environments, as well as from other parts of the organization, elicit particular cognitive responses, conditional upon the *collective mental models* that the organization holds. Cognitive memory maps signals from an otherwise unknown world into cognitive states (this year the state of the market is such that it will be profitable to produce X). Conversely, the operational memory elicits operating routines in response to cognitive states (“this year we should produce X”), internal states of the organization (“the machines are ready to start producing piece P”) and also environmental feedbacks (“after all X is not selling too well”).

Cognitive and operational memories entail an *if* → *then* structure. A promising candidate to model them finds its roots into the formalism of classifier systems (Holland, 1975, 1986): a pioneering application developed in Marengo, (1992) and subsequent refinements in Dosi et al., (2017). On the ground of such formal apparatus one can first analyze the effects in terms of performances of different distributions of knowledge and of the related memory elements within the organization (e.g. whether hierarchically versus horizontally distributed, etc...) conditional upon different characteristics of the environment. Second, this type of models may help to explore the conjecture – well grounded in several empirical studies – that a memory structure well “fit” for a particular environment may turn out to be pernicious under different technological or market conditions (cf. among others Tripsas and Gavetti, 2000 and Bresnahan et al., 2011). In fact, in many respects, much work has still to be done in the exploration of the outcomes of the mappings between types of knowledge, memory characteristics, organizational architectures and patterns of environmental change.

3.3 Corporate Learning, Competition and Industrial Evolution

In modern capitalism, business firms are a central locus of the efforts to advance technologies, develop new products and operate new production processes. Thus the knowledge and the procedures underlying each technology, discussed in the previous section, are to a good extent embodied in organizational routines and other “quasi genetic action patterns” of organizations (Winter in Cohen et al., 1996).

Indeed, an emerging capability-based theory of the firm (cf. Dosi et al., 2001; Dosi et al., 2008 among others) places the “primitives” of the nature of business firms in their problem-solving features, that is their abilities to address practical and cognitive problems, ranging from, say, the production of a car to the identification of a malaria-curing molecules.

The approach, which finds its roots in the works of H. Simon, J. March, A. Chandler and S. Winter - fully acknowledging ubiquitous forms of human bounded rationality, grossly imperfect processes of learning and diverse social distributions of cognitive labour - attempts to identify the distinctive capabilities of organizations as emergent from their distinctive ensembles of organizational routines. And, dynamically, the approach tries to account for the processes by which organizational knowledge is acquired, maintained, augmented and sometimes lost - partly as a result of the *dynamic capabilities* of organization themselves (Teece et al., 1997; Helfat, 2007).

Idiosyncratic capabilities and, dynamically, idiosyncratic patterns of learning by firms are the general rule. In turn, such persistently heterogeneous firms are nested in competitive environments, which shape their individual economic fate and, collectively, the evolution of the forms of industrial organization. Differences in products and in processes of production - and as a consequence costs and prices - are central features of the competitive process in which firms are involved in different ways. Let us call Schumpeterian competition the process through which heterogeneous firms compete on the basis of the products and services they offer and obviously their prices, and get selected - with some firms growing, some declining, some going out of business, some new ones always entering. Such processes of competition and selection are continuously fuelled by the activities of innovation, adaptation, imitation by incumbent firms and by entrants. In turn, the processes of industrial evolution leaves statistical footprints in terms of industrial structures and firm dynamics. Thanks to massive infusions of micro-data over the last 20 years, one has begun to identify a few robust statistical properties characterizing industrial structures, their changes, and performance indicators.

In general, evolutionary interpretations are grounded on two basic building blocks. The first is a learning part wherein individual agents (firms), massively boundedly rational but always able to innovate, search for new techniques and new products and the second is a selection part whereby market interactions determine ex-post profitabilities, survival probabilities and firm rates of growth. More on the structure of evolutionary models of industrial dynamics in Silverberg et al., (1988) and Silverberg and Lehnert, (1994) Metcalfe, (1998) Dosi et al., (1995, 2015b).

The (idiosyncratic) learning part of the dynamics is often represented as a stochastic search for innovation and imitation in the neighbourhood of the incumbent techniques of each firm. Conversely, the selection part of the process is basically captured by different instantiations of some replication dynamics. The bottom line is a relation between some corporate characters - that is, technological, organizational, or behavioural traits - which the particular interactive environment favours, on the one hand, and the rate of variation of the frequencies in the carriers of such characters in the relevant populations on the other.

One has only begun to systematically link evolutionary models with the stylized facts of industrial dynamics discussed above. Here the big challenge regards the ability of the models of generating - and in that sense explaining - the rich ensembles of observed empirical regularities, both those that are generic, holding across sectors, countries and phases of the industry life cycles, and those that are regime-specific. In that the phenomena to be explained - ranging from size distributions and other measures of industrial structures such as concentration, to the distributions of corporate growth rates all the way to the determinants of growth itself - ought to be understood, again, as emergent properties stemming from the out-of-equilibria interaction of heterogeneous, far from omniscient, but potentially innovative, agents.

In particular, to date, the generality of evolutionary models has assumed some monotonicity in the relations between fundamental determinants of competitiveness/revealed fitness, and subsequent relative growth. However, the evidence on these selective processes suggests that selection forces are weaker than those theorised. In turn, this may well be the consequence of various forms of market imperfections - including informational ones - which, together with endemic satisfying behaviours, allow firms characterized by diverse degrees of efficiency and product qualities to co-exist without too much relative pressure. On the modelling side such evidence demands an account of evolution occurring over multidimensional fitness landscapes - explicitly capturing the multidimensional differences in product characteristics - rugged, thus allowing for multiple metastable states, but also intertwined by ample flat areas - whereby selective pressures are relatively low.

3.4 From micro to macro coordination and growth

We have already discussed above that the interpretation of macroeconomic dynamics must have, in our view, micro-foundations explicitly resting on multiplicity of heterogeneous interacting agents. Granted that, there are two complementary modelling perspectives.

In a first one, which we could call *coordination without evolution*, one may study the condition under which coordination emerges, intertwined by major phase changes, in markets, and other interacting environments, wherein agents interact and adjust locally. The *fundamentals* of such environments might well be stationary (hence, strictly speaking, no evolution), but the thread of interactions and adjustments typically yields non linear macroscopic effects characterized by diverse patterns of coordination (or lack of it). A lot of work has been done in this perspective (for surveys, see Tesfatsion and Judd, 2006 and LeBaron and Tesfatsion, 2008) offering theoretical tales on self-organizing patterns. Still, one is quite far from a thorough understanding of how markets work, conditional on their different network structures, as convincingly advocated by Kirman, (2011).

Together, let us strongly urge the investigation of *coordination with evolution* on the ground of higher dimensional, phenomenologically much richer Agent Based Models. Within a growing ensemble of ABM efforts (see Fagiolo and Roventini, 2016 for a recent survey), the authors of this note intend to proceed in refining and

developing upon the family of “Schumpeter meeting Keynes” models (Dosi et al., 2013, 2015a, 2010, 2016a,b). They clearly meet Solow, (2008)’s plea for micro-heterogeneity: a multiplicity of agents interact without any ex ante commitment to the reciprocal consistency of their actions.

This family of models bridges Keynesian theories of demand generation and Schumpeterian theories of technology-fuelled economic growth. Agents always face opportunities of innovations and imitation, which they try to tap with expensive search efforts, under conditions of genuine uncertainty (so they are unable to form any accurate expectations on the relation between search investment and probabilities of successful outcomes). Hence (endogenous) technological shocks (the innovations themselves) are unpredictable and idiosyncratic.

This family of models builds on evolutionary roots, but is also in tune with genuine Keynesian insights. It tries to explore the feedbacks between the factors influencing aggregate demand and those driving technological change. By doing that, it begins to offer a unified framework jointly accounting for long-term dynamics and higher frequencies fluctuations. The model is “structural” in the sense that it explicitly builds on a representation of what agents do, how they adjust, how they interact and respond to policy changes. Indeed, the model has already proved to be able to generate jointly, as emergent properties, a wide set of stylized facts regarding both micro/meso phenomena and macro stylized facts. They include (i) endogenous growth; (ii) persistent fluctuations; (iii) recurrent involuntary unemployment; (iv) pro-cyclical consumption, investment, productivity, employment and changes in inventories; (v) fat-tailed distributions of aggregate growth rates; together with persistent asymmetries in productivity across firms; (vi) spiky investment patterns; (vii) skewed firm size distributions; (viii) fat-tailed firm growth rates, and (ix) on the labour market side Beveridge, Wage (or Phillips), and Okun curves, (x) separation and hiring rates volatility, (xi) matching function, (xii) productivity, unemployment and vacancy rates volatility, (xiii) unemployment and inequality correlation (cf. Dosi et al., 2016b). To repeat, the foregoing robust statistical regularities and relatively stable relations amongst aggregate variables do indeed emerge out of turbulent, disequilibrium, microeconomic interactions. As such, the model can be used also as sort of “laboratory” for policy experiments. We have begun to do it, showing, for example, the complementarity between Keynesian and Schumpeterian policies.

4 Some challenges ahead, by way of a conclusion

In these notes we have tried to offer an evolutionary view on, possibly, the two major questions which cut across the whole history of economics as a discipline, namely the drivers of change and the coordinating properties of a system composed by multiple interacting agents. In many ways, they are a sort of advocacy of “back to the classics”, especially Smith, Malthus and Marx, albeit with much more sophisticated formal and computational instruments. The basic interpretative conjecture here is that the properties we observe stem from the fact that the capitalist economies are the first ones in human history which incessantly “change from within”. And it is

this very feature which accounts for the relatively orderly interactions which one often observes.

There is a lot that is there to be done on the theory side. And even more so, it has to be done on sides of statistics and of theory-informed, qualitative, historical interpretation, what Nelson and Winter, (1982) call “appreciative theorizing”. Just to name a few domains.

Some challenges were already there in the largely unfilled “Santa Fe complexity programme” (see the introduction by Pines to Anderson et al., 1988). For example, *first* how do agents behave and learn in complex evolving environments? Economics, especially over the last half a century, has put an overwhelming emphasis on expectations in the interpretation of behaviour, unique in all disciplines, which matured beyond “Aristotelian” final causes. But that, in turns, implies a universally, transparent present and future, which is hardly in tune with innovation-ridden evolutionary worlds.

Second, how does one formally accounts for evolutionary processes wherein the dimensionality of the state-space progressively evolve?

Third, even short of that current econometric techniques are postulated upon unique equilibrium states shocked by exogenous disturbances. But, what if there are e.g. non-linear dynamics with multiple local attractors, persistently perturbed by endogenously generated shocks, how do we account for them?

Forth, and well beyond the Santa Fe programme, what is the theory of value and income distribution in knowledge intensive worlds, generally characterised by increasing returns? Note, in this respect, that if one loses convexity in production plans, one loses also the link between the theory of production and the theory of income distribution. In our view, this is just a good news, but it poses a problem also for classical, cost-based theories: what is the value of a Microsoft software or a drug: whenever the cost of replication is minor, is it just proportional to the cost of engineers and scientists who generated them?

The list is far from being exhaustive. And this is matched by equally important (or even more important) interpretative issues which have to do with the contemporary dynamics of capitalist economies.

A *first* one concerns labour market, wages and employment. The innovation-employment nexus deserves overriding attention. In the wake of a potential fourth Industrial Revolution, of a debate on productivity decline, “secular stagnation” and future robotization, research addressing the effects on both the quantity and the quality of employment is needed, as well as the balance between product and process innovation in terms of employment creation-destruction.

A *second* related one is inequality. It is and will be the core topic, together with unemployment, of the next many years. Even though the post-crisis period has been marked by an overwhelming and blossoming literature on inequality, still detailed studies looking inside the transformation at work-floor, the wage determination processes, the organization of the industrial relations, the process of de-unionisation are partly missing and badly needed. Beside that, what do we know about the potential link between productivity and wage dispersion, as possible determining

mechanisms causing wage inequality, as compared to other mechanisms such as globalization and the financialization of the economies?

On the modelling side, the Schumpeter meeting Keynes model leaves scope for many potential avenues for further research: (i) the analysis of the effect of long-term versus short-term labour contracts on firm productivity, digging inside the impact of contract duration on the process of workers skills accumulation, and consequently on productivity; (ii) a north-south version direct at studying the effect of flows of capital goods, consumption goods and workers among two countries, a leading and a lagging one, analysing the emergence of patterns of product specialization vis-à-vis diversification, cost-competitiveness vis-à-vis technological competitiveness, growth convergence vis-à-vis divergence; (iii) the effect of product vis-à-vis process innovation in terms of creation/destruction of labour demand.

And last but not least, policy analyses involve a fundamental paradigmatic change: the central concern for policies ought to shift away from efficient allocation issues, to the (imperfect) governance of coordination (Kirman, 2011), and of genuinely uncertain processes of change.

References

- Abramovitz, M. (1956). “Resource and output trends in the United States since 1870”. In: *Resource and output trends in the United States since 1870*. NBER, 1–23.
- Anderson, P.W., K. Arrow, and D. Pines (1988). *The economy as a complex evolving system*. Addison-Wesley.
- Arrow, K. (1996). “Technical Information and Industrial Structure”. *Industrial and Corporate Change* 5.2, 645–52.
- Becker, G. (1962). “Irrational behavior and economic theory”. *The Journal of Political Economy*, 1–13.
- Becker, G. (1976). “Altruism, Egoism, and Genetic Fitness: Economics and Sociobiology”. *Journal of Economic Literature* 14.3, 817–26.
- Boyer, R. (1988). “Technical change and theory of ‘Régulation’”. In: *Technical change and Economic theory*. Ed. by G. Dosi, C. Freeman, R. Nelson, G Silverberg, and L. Soete. Pinter Publisher, London and New York, 67–94.
- Bresnahan, T., S. Greenstein, and R. Henderson (2011). “Schumpeterian competition and diseconomies of scope: illustrations from the histories of Microsoft and IBM”. In: *The rate and direction of inventive activity revisited*. Ed. by J. Lerner and S. Stern. University of Chicago Press, 203–271.
- Brock, W. (1999). “Scaling in economics: a reader’s guide”. *Industrial and Corporate change* 8.3, 409–446.
- Camazine, S. et al. (2001). *Self-organization in biological systems*. Princeton University Press.
- Cohen, M., R. Burkhart, G. Dosi, M. Egidi, L. Marengo, M. Warglien, and S. Winter (1996). “Routines and other recurring action patterns of organizations: contemporary research issues”. *Industrial and corporate change* 5.3, 653–698.

- David, P. (1985). “Clio and the Economics of QWERTY”. *The American economic review* 75.2, 332–337.
- DeMiguel, V., L. Garlappi, and R. Uppal (2009). “Optimal Versus Naive Diversification: How Inefficient is the 1/N Portfolio Strategy?” *Review of Financial Studies* 22.5, 1915–1953.
- Dosi, G. (1982). “Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change”. *Research policy* 11.3, 147–162.
- Dosi, G. (1984). “Technology and conditions of macroeconomic development”. In: *Design, Innovation and Long Cycles in Economic Development*. Ed. by C. Freeman. London: Design Research Publications, 99–125.
- Dosi, G. (1988). “Sources, Procedures, and Microeconomic Effects of Innovation”. *Journal of Economic Literature* 26.3, 1120–1171. ISSN: 00220515.
- Dosi, G. (2012). *Economic Coordination and Dynamics: Some Elements of an Alternative Evolutionary Paradigm*. LEM Papers Series 2012/08. Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies, Pisa, Italy.
- Dosi, G. and M. Egidi (1991). “Substantive and procedural uncertainty”. *Journal of Evolutionary Economics* 1.2, 145–168. ISSN: 1432-1386.
- Dosi, G., G. Fagiolo, M. Napoletano, and A. Roventini (2013). “Income distribution, credit and fiscal policies in an agent-based Keynesian model”. *Journal of Economic Dynamics and Control* 37.8, 1598–1625.
- Dosi, G., G. Fagiolo, M. Napoletano, A. Roventini, and T. Treibich (2015a). “Fiscal and monetary policies in complex evolving economies”. *Journal of Economic Dynamics and Control* 52, 166–189.
- Dosi, G., G. Fagiolo, and A. Roventini (2010). “Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles”. *Journal of Economic Dynamics and Control* 34.9, 1748–1767.
- Dosi, G., M. Faillo, and L. Marengo (2008). “Organizational capabilities, patterns of knowledge accumulation and governance structures in business firms: An introduction”. *Organization Studies* 29.8-9, 1165–1185.
- Dosi, G., D. A Levinthal, and L. Marengo (2003). “Bridging contested terrain: linking incentive-based and learning perspectives on organizational evolution”. *Industrial and Corporate Change* 12.2, 413–436.
- Dosi, G. and L. Marengo (2015). “The dynamics of organizational structures and performances under diverging distributions of knowledge and different power structures”. *Journal of Institutional Economics* 11.03, 535–559.
- Dosi, G., L. Marengo, E. Paraskevopoulou, and M. Valente (2017). “A model of cognitive and operational memory of organizations in changing worlds”. *Cambridge Journal of Economics*. Forthcoming.
- Dosi, G., O. Marsili, L. Orsenigo, and R. Salvatore (1995). “Learning, market selection and the evolution of industrial structures”. *Small Business Economics* 7.6, 411–436.
- Dosi, G., R. Nelson, and S. Winter (2001). *The nature and dynamics of organizational capabilities*. OUP Oxford.

- Dosi, G., M. C. Pereira, A. Roventini, and M. E. Virgillito (2016a). *The Effects of Labour Market Reforms upon Unemployment and Income Inequalities: an Agent Based Model*. LEM Papers Series 2016/27. Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies, Pisa, Italy.
- Dosi, G., M. C. Pereira, A. Roventini, and M. E. Virgillito (2016b). *When more Flexibility Yields more Fragility: the Microfoundations of Keynesian Aggregate Unemployment*. LEM Papers Series 2016/06. Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies, Pisa, Italy.
- Dosi, G., M.C. Pereira, and M.E. Virgillito (2015b). *The footprint of evolutionary processes of learning and selection upon the statistical properties of industrial dynamics*. LEM Papers Series 2015/04. Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies, Pisa, Italy.
- Dosi, G. and M. E. Virgillito (2016). *The “Schumpeterian” and the “Keynesian” Stiglitz: Learning, Coordination Hurdles and Growth Trajectories*. Lem Working Paper Series 2016/20. Scuola Superiore Sant’Anna, Pisa.
- Dosi, G. and S. Winter (2002). “Interpreting economic change: evolution, structures and games”. In: *The Economic of Choice, Change and organization. Essays in Memory of Richard M. Cyert*. Ed. by M. Augier and J. March. Edward Elgar, Cheltenham.
- Fagiolo, G. and A. Roventini (2016). *Macroeconomic Policy in DSGE and Agent-Based Models Redux: New Developments and Challenges Ahead*. LEM Working Paper 2016/17. Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies, Pisa, Italy.
- Fogel, R. (1965). “The reunification of economic history with economic theory”. *The American Economic Review* 55.1/2, 92–98.
- Freeman, C. and F. Louçã (2001). *As Time Goes By: From the Industrial Revolutions to the Information Revolution: From the Industrial Revolutions to the Information Revolution*. OUP Oxford.
- Gigerenzer, G. and W. Gaissmaier (2011). “Heuristic decision making”. *Annual review of psychology* 62, 451–482.
- Goodwin, R. (1951). “The nonlinear accelerator and the persistence of business cycles”. *Econometrica* 19, 1–17.
- Grandmont, J. (1991). *Transformations of the Commodity Space, Behavioral Heterogeneity and the Aggregation Problem*. Cowles Foundation Discussion Papers 987. Cowles Foundation for Research in Economics, Yale University.
- Helfat, C. (2007). “Stylized facts, empirical research and theory development in management”. *Strategic Organization* 5.2, 185–192.
- Hildenbrand, W. (1994). *Market demand: Theory and empirical evidence*. Princeton University Press.
- Holland, J. (1975). *Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence*. University of Michigan Press.
- Holland, J. (1986). “Escaping brittleness: the possibilities of general purpose learning algorithms applied to parallel rule-based system”. *Machine learning*, 593–623.

- Kahneman, D. (2002). *Maps of bounded rationality: a perspective on intuitive judgment and choice*. Nobel laureate acceptance speech.
- Kaldor, N. (1940). "A Model of the Trade Cycle". *The Economic Journal* 50, 78–92.
- Kirman, A. (1992). "Whom or what does the representative individual represent?" *The Journal of Economic Perspectives* 6.2, 117–136.
- Kirman, A. (2011). *Complex Economics. Individual and Collective Rationality*. Routledge, London.
- Kirman, A. (2016). "Complexity and Economic Policy: A Paradigm Shift or a Change in Perspective? A Review Essay on David Colander and Roland Kupers's Complexity and the Art of Public Policy". *Journal of Economic Literature* 54.2, 534–572.
- Landes, D. (1969). *The unbound Prometheus: technological change and industrial development in Western Europe from 1750 to the present*. Cambridge University Press, London.
- Landes, D. (1994). "What room for accident in history?: explaining big changes by small events". *The Economic History Review* 47.4, 637–656.
- Lane, D. (1993). "Artificial worlds and economics, part I". *Journal of Evolutionary Economics* 3.2, 89–107.
- LeBaron, B. and L. Tesfatsion (2008). "Modeling macroeconomics as open-ended dynamic systems of interacting agents". *The American Economic Review* 98.2, 246–250.
- Levitt, B. and J. March (1988). "Organizational learning". *Annual review of sociology*, 319–340.
- March, J. G. (1962). "The business firm as a political coalition". *The Journal of Politics* 24.04, 662–678.
- Marengo, L. (1992). "Coordination and organizational learning in the firm". *Journal of Evolutionary Economics* 2.4, 313–326.
- Marengo, L. and G. Dosi (2005). "Division of labor, organizational coordination and market mechanisms in collective problem-solving". *Journal of Economic Behavior & Organization* 58.2, 303–326.
- Marshall, A. (1890). *Principles of Economics*. London: Macmillan.
- Mas-Colell, A., M. Whinston, and J. Green (1995). *Microeconomic theory*. Vol. 1. Oxford university press.
- Metcalf, J. S. (1998). *Evolutionary Economics and Creative Destruction*. Routledge.
- Nelson, R. (1993). *National innovation systems: a comparative analysis*. Oxford university press.
- Nelson, R. (2016). "An overview of modern evolutionary economics". mimeo.
- Nelson, R. and S. Winter (1982). *An Evolutionary Theory of Economic Change*. Harvard:Harvard University Press.
- Nicolis, G. and I. Prigogine (1977). *Self-organization in nonequilibrium systems: from dissipative structures to order through fluctuations*. Wiley & Sons, New York.
- Pasinetti, L. (1960). "Cyclical Fluctuations and Economic Growth". *Oxford Economic Papers* 12, 215–241.

- Radner, R. and J. Stiglitz (1984). “A Nonconcavity in the Value of Information”. In: *Bayesian Models in Economic Theory: Studies in Bayesian Econometrics*. Ed. by M. Boyer and R. Kihlstrom. Vol. 5. Elsevier Science Publications, 421–452.
- Rosenberg, N. (1982). *Inside the black box: technology and economics*. Cambridge University Press, London.
- Rothschild, M. and J. Stiglitz (1976). “Equilibrium in Competitive Insurance Markets: An Essay on the Economics of Imperfect Information”. *The Quarterly Journal of Economics* 90.4, 629–649.
- Schumpeter, J. (1947). *Capitalism, Socialism, and Democracy*. New York and London: Harper & Brothers Publishers.
- Shaikh, A. (2012). *Rethinking Microeconomics: A Proposed Reconstruction*. Working Papers 1206. New School for Social Research, Department of Economics.
- Silverberg, G., G. Dosi, and L. Orsenigo (1988). “Innovation, diversity and diffusion: a self-organisation model”. *The Economic Journal* 98.393, 1032–1054.
- Silverberg, G. and D. Lehnert (1994). “Growth Fluctuations in an Evolutionary model of Creative Destruction”. In: *The Economics of Growth and Technical Change: Technologies, Nations, Agents*. Ed. by G. Silverberg and L. Soete. Edward Elgar Publishing Ltd., Aldershot, 74–108.
- Silverberg, G. and B. Verspagen (1994). “Learning, Innovation and Economic Growth: A Long-run Model of Industrial Dynamics”. *Industrial and Corporate Change* 3.1, 199–223.
- Simon, H. (1969). *The Science of the Artificial*. MA: MIT Press.
- Simon, H. (1979). “Rational Decision Making in Business Organizations”. *The American Economic Review* 69.4, 493–513.
- Solow, R. (2008). “The state of macroeconomics”. *Journal of Economic Perspectives* 22, 243–246.
- Teece, D., G. Pisano, and A. Shuen (1997). “Dynamic Capabilities and Strategic Management”. *Strategic Management Journal* 18.7, 509–33.
- Tesfatsion, L. and K. Judd (2006). *Handbook of computational economics: agent-based computational economics*. Vol. 2. Elsevier.
- Tripsas, M. and G. Gavetti (2000). “Capabilities, cognition, and inertia: Evidence from digital imaging”. *Strategic management journal* 21.10-11, 1147–1161.
- Winter, S. (1964). “Economic” natural selection” and the theory of the firm”. *Yale Economic Essays* 4.1, 224–272.
- Winter, S. (1971). “Satisficing, Selection, and the Innovating Remnant”. *The Quarterly Journal of Economics* 85.2, 237–261.
- Winter, S. (2016). *Pursuing the Evolutionary Agenda in Economics and Management Research*. LEM Papers Series 2016/22. Laboratory of Economics and Management (LEM), Sant’Anna School of Advanced Studies, Pisa, Italy.